ABSTRACT ITA
Questa tesi conduce un esame rigoroso della capacità del design architettonico di mitigare gli impatti ambientali, con un focus specifico sull'evoluzione concettuale verso gli 'edifici positivi'. Esamina criticamente se il concetto debba essere limitato alla positività energetica—dove gli edifici producono più energia di quella che consumano—o debba includere uno spettro più ampio di impatti ambientali netti positivi. La ricerca analizza sistematicamente il ruolo della geometria degli edifici e dei materiali di rivestimento innovativi nel promuovere questi obiettivi. Impiegando un grande edificio per uffici a Boston come prototipo, illustra le implicazioni pratiche e valuta l'efficacia delle strategie di progettazione proposte, mettendo in discussione la fattibilità e la praticità di obiettivi così ambiziosi.

ABSTRACT ENG
This dissertation conducts a rigorous examination of the capacity of architectural design to mitigate environmental impacts, with a specific focus on the conceptual evolution towards 'positive buildings.' It critically examines whether the concept should be confined to energy positivity—where buildings produce more energy than they consume—or should encompass a broader spectrum of net positive environmental impacts. The research systematically analyzes the role of building geometry and innovative cladding materials in advancing these objectives. Employing a large office building in Boston as a prototype, it illustrates the practical implications and evaluates the effectiveness of the proposed design strategies while questioning the feasibility and practicality of such ambitious goals.

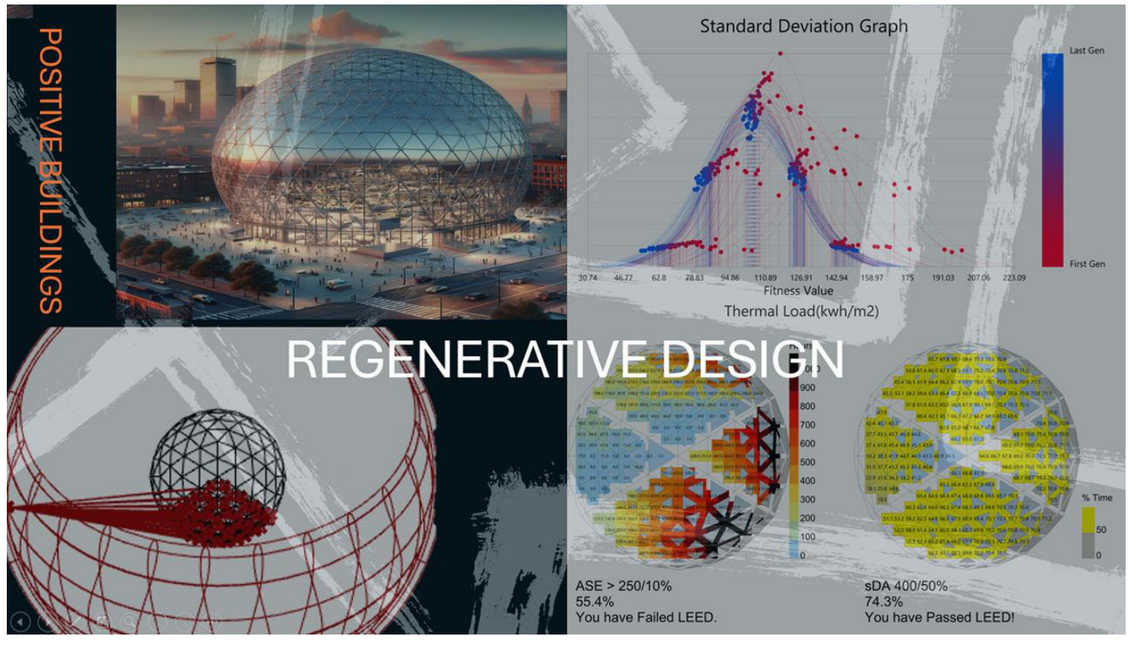
ARCHITECTURAL PRINCIPLES FOR DESIGNING SPATIAL STRUCTURES TO ADDRESS POSITIVE BUILDINGS Zinat Javanmard

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Zinat Javanmard

ARCHITECTURAL PRINCIPLES FOR DESIGNING SPATIAL STRUCTURES TO ADDRESS POSITIVE BUILDINGS

A COMPARATIVE ENVIRONMENTAL IMPACT ASSESSMENT OF GEOMETRIC FORMS AND SUSTAINABLE CLADDING MATERIALS IN POSITIVE SPATIAL STRUCTURE DESIGN



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BIO



Zinat Javanmard, a PhD candidate at Mediterranea University, specializes in regenerative design and positive buildings within the ABITA lab. Holding master's degrees in architecture and structural engineering, focusing on spatial structures from Iran, Zinat pursued advanced studies to deepen her expertise in sustainable architectural practices. Serving as a Visiting Ph.D. Fellow (Marie Skłodowska-Curie) at the Department of Economics, Northeastern University, Zinat enriched her understanding of sustainable design and the environmental impact of buildings. This thesis is the culmination of her studies at Mediterranea University and Northeastern University in the field of transformative design. Her tenure has been instrumental in shaping her research, resulting in several notable publications in the field.

ZINAT JAVANMARD

ARCHITECTURAL PRINCIPLES FOR REGENERATIVE DESIGN OF SPATIAL STRUCTURES TO ADDRESS POSITIVE BUILDINGS

A COMPARATIVE ENVIRONMENTAL IMPACT ASSESSMENT OF GEOMETRIC FORMS AND SUSTAINABLE CLADDING MATERIALS IN POSITIVE SPATIAL STRUCTURE DESIGN

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Abstract

This dissertation conducts a rigorous examination of the capacity of architectural design to mitigate environmental impacts, with a specific focus on the conceptual evolution towards 'positive buildings.' It critically examines whether the concept should be confined to energy positivity—where buildings produce more energy than they consume—or should encompass a broader spectrum of net positive environmental impacts. The research systematically analyzes the role of building geometry and innovative cladding materials in advancing these objectives. Employing a large office building in Boston as a prototype, it illustrates the practical implications and evaluates the effectiveness of the proposed design strategies while questioning the feasibility and practicality of such ambitious goals.

The research employs a dual-section methodology to assess the environmental impacts of various building geometries and cladding materials, with a particular focus on operational energy consumption and its influence on indoor comfort conditions. In Section One, the study meticulously examines how different geometric configurations—namely the Cask, Sphere, and Cube—affect environmental sustainability through their energy usage. This analysis leverages advanced design tools such as Rhino and Grasshopper for parametric modeling, complemented by Honeybee and Ladybug for comprehensive energy analysis and climatic adaptation. Additionally, data-driven approaches via OpenLCA, including the life cycle assessment of "Market low-voltage electricity—Cutoff_U", are utilized since the energy for cooling and heating systems in Boston is predominantly supplied through this process. This methodology provides a detailed evaluation of each form's performance during the operational phase.

The integration of machine learning with the design process marks the next step in advancing the methodology. The application of Python enhances sensitivity analysis, enabling a deeper understanding of which design variables significantly affect environmental impacts. Notably, the Sphere demonstrates a significant reduction in environmental impact by 30.81% compared to the Cube and Cask, with sensitivity analysis highlighting the critical influence of the sphere's radius on its energy performance. Similarly, the length and height are identified as pivotal design variables for the Cube and Cask, respectively. This process is further enriched by the integration of Python-based machine learning algorithms, specifically Random Forest and Extreme Gradient Boosting, which play a crucial role in identifying and understanding the sensitivity of design variables to environmental impacts.

To address the sub question regarding the impact of various environmental categories, normalization based on CO_2 equivalence was conducted using TRACI 2.1 normalization factors, calculated from US 2008 inventory data (OpenLCA, ecoinvent 3.6). The analysis identified fossil fuel usage as the most critical category, followed by impacts on global warming, ecotoxicity, and smog in terms of CO_2 emissions.

This methodology not only showcases the robust application of Python in an architectural context but also underscores the practical implications of machine learning in optimizing building design for reduced environmental impact. By focusing

on the strategic manipulation of design variables, this study contributes significantly to the field of sustainable architectural practices, providing actionable insights for the design of energy-efficient and environmentally friendly buildings.

The second section of the study shifts focus to material analysis, comparing aluminum, polycarbonate, and hybrid cladding systems using environmental modeling tools. Similar to Section One, this analysis employs Rhino and Grasshopper for parametric modeling, and Ladybug and Honeybee for energy analysis and climatic design. Additionally, OpenLCA is utilized to calculate the environmental impact categories. The materials selected for this analysis are accompanied by Environmental Product Declarations (EPDs) to ensure that other life cycle stages are accounted for, thereby enabling more accurate results. The detailed energy consumption data reveals that polycarbonate cladding consumes significantly more energy than aluminum, with 93.3% higher usage for cooling and 80.7% more for heating, while polycarbonate is substantially more efficient in lighting, using 66.19% less energy than Aluminum. These variations in energy consumption reflect corresponding changes in environmental pollutants during the B6 stage. Alone, neither system met the LEED certification standards for both Annual Sunlight Exposure (ASE) and Spatial Daylight Autonomy (sDA). In response, a hybrid system was developed and optimized using the NSGA-2 algorithm, Wallacei's selection methods, and Design Explorer, achieving a more balanced performance with an sDA of 54.7% and an ASE of 7.3%, suggesting an optimal solution for meeting LEED standards. The findings from both sections are synthesized to formulate architectural design principles that prioritize sustainability and environmental Impacts based on energy usage.

The combined findings lead to the formulation of design principles that not only prioritize reducing environmental impacts and energy usage but also explore the cautious and incremental adoption of strategies towards realizing positive buildings. This research proposes a framework for employing data-driven approaches, including machine learning, to refine predictions and enhance building performance, aiming to make architectural design more responsive to environmental sustainability.

In conclusion, the thesis engages in a measured discussion on the potential and challenges of achieving positive buildings, questioning the level of optimism surrounding this concept and critically assessing the barriers to its practical realization.

Sintesi

Questa tesi conduce un esame rigoroso della capacità del design architettonico di mitigare gli impatti ambientali, con un focus specifico sull'evoluzione concettuale verso gli 'edifici positivi'. Esamina criticamente se il concetto debba essere limitato alla positività energetica—dove gli edifici producono più energia di quella che consumano—o debba includere uno spettro più ampio di impatti ambientali netti positivi. La ricerca analizza sistematicamente il ruolo della geometria degli edifici e dei materiali di rivestimento innovativi nel promuovere questi obiettivi. Impiegando un grande edificio per uffici a Boston come prototipo, illustra le implicazioni pratiche e valuta l'efficacia delle strategie di progettazione proposte, mettendo in discussione la fattibilità e la praticità di obiettivi così ambiziosi.

La ricerca impiega una metodologia a doppia sezione per valutare gli impatti ambientali di varie geometrie edilizie e materiali di rivestimento, con particolare attenzione al consumo energetico operativo e alla sua influenza sulle condizioni di comfort interno. Nella Sezione Uno, lo studio esamina meticolosamente come diverse configurazioni geometriche — specificamente il Cask, la Sfera e il Cubo — influenzino la sostenibilità ambientale attraverso l'uso dell'energia. Questa analisi si avvale di strumenti di progettazione avanzati come Rhino e Grasshopper per la modellazione parametrica, integrati da Honeybee e Ladybug per l'analisi energetica e l'adattamento climatico. Inoltre, approcci guidati dai dati attraverso OpenLCA, inclusa la valutazione del ciclo di vita dell'energia elettrica a bassa tensione—Cutoff_U (poiché l'energia per i sistemi di riscaldamento e raffreddamento a Boston è prevalentemente fornita da questo processo), forniscono una valutazione completa delle prestazioni di ciascuna forma durante la fase operativa.

L'integrazione dell'apprendimento automatico con il processo di progettazione segna il passo successivo nell'avanzamento della metodologia. L'applicazione di Python migliora l'analisi di sensibilità, consentendo una comprensione più profonda di quali variabili di design influenzano significativamente gli impatti ambientali. In particolare, la Sfera dimostra una riduzione notevole dell'impatto ambientale del 30,81% rispetto al Cubo e al Cask, con un'analisi di sensibilità che evidenzia l'influenza critica del raggio della sfera sulle sue prestazioni energetiche. Analogamente, la lunghezza e l'altezza sono identificate come variabili di design cruciali per il Cubo e il Cask, rispettivamente. Questo processo è ulteriormente arricchito dall'integrazione di algoritmi di machine learning basati su Python, in particolare Random Forest e Extreme Gradient Boosting, che svolgono un ruolo cruciale nell'identificare e comprendere la sensibilità delle variabili di design agli impatti ambientali.

Per affrontare la sotto-questione riguardante l'impatto di varie categorie ambientali, è stata condotta una normalizzazione basata sull'equivalenza di CO_2 utilizzando i fattori di normalizzazione TRACI 2.1, calcolati dai dati di inventario degli USA del 2008 (OpenLCA, ecoinvent 3.6). L'analisi ha identificato l'uso dei combustibili fossili come categoria più critica, seguita dagli impatti sul riscaldamento globale, l'ecotossicità e lo smog in termini di emissioni di CO_2.

Questa metodologia non solo mette in evidenza l'applicazione robusta di Python nel contesto architettonico ma sottolinea anche le implicazioni pratiche dell'apprendimento automatico nell'ottimizzare la progettazione degli edifici per ridurre l'impatto ambientale. Concentrandosi sulla manipolazione strategica delle variabili di design, questo studio contribuisce significativamente al campo delle pratiche architettoniche sostenibili, offrendo spunti concreti per la progettazione di edifici energeticamente efficienti e ecocompatibili.

La seconda sezione dello studio sposta l'attenzione sull'analisi dei materiali, confrontando sistemi di rivestimento in alluminio, policarbonato e ibridi utilizzando strumenti di modellazione ambientale. Similmente alla Sezione Uno, questa analisi impiega Rhino e Grasshopper per la modellazione parametrica, e Ladybug e Honeybee per l'analisi energetica e il design climatico. Inoltre, OpenLCA è utilizzato per calcolare le categorie di impatto ambientale. I materiali selezionati per questa analisi sono accompagnati da Dichiarazioni Ambientali di Prodotto (EPD) per garantire che anche altre fasi del ciclo di vita siano considerate, consentendo così risultati più accurati. I dati dettagliati sul consumo energetico rivelano che il rivestimento in policarbonato consuma significativamente più energia rispetto all'alluminio, con un uso del 93,3% maggiore per il raffreddamento e dell'80,7% in più per il riscaldamento, mentre il policarbonato è sostanzialmente più efficiente nell'illuminazione, utilizzando il 66,19% di energia in meno rispetto all'Alluminio. Queste variazioni nel consumo energetico riflettono cambiamenti corrispondenti negli inquinanti ambientali durante la fase B6. Da soli, nessuno dei sistemi ha soddisfatto gli standard di certificazione LEED per l'Esposizione Solare Annuale (ASE) e l'Autonomia di Illuminazione Spaziale (sDA). In risposta, è stato sviluppato e ottimizzato un sistema ibrido utilizzando l'algoritmo NSGA-2, i metodi di selezione di Wallacei e Design Explorer, ottenendo prestazioni più bilanciate con un sDA del 54,7% e un ASE del 7,3%, suggerendo una soluzione ottimale per soddisfare gli standard LEED. I risultati di entrambe le sezioni sono sintetizzati per formulare principi di progettazione architettonica che danno priorità alla sostenibilità e agli impatti ambientali basati sull'uso dell'energia.

I risultati combinati portano alla formulazione di principi di design che non solo danno priorità alla riduzione degli impatti ambientali e all'uso dell'energia ma esplorano anche l'adozione cauta e incrementale di strategie verso la realizzazione di edifici positivi. Questa ricerca propone un quadro per l'impiego di approcci basati sui dati, inclusi l'apprendimento automatico, per affinare le previsioni e migliorare le prestazioni degli edifici, mirando a rendere il design architettonico più responsivo alla sostenibilità ambientale.

In conclusione, la tesi si impegna in una discussione misurata sul potenziale e sulle sfide nel raggiungere edifici positivi, mettendo in discussione il livello di ottimismo intorno a questo concetto e valutando criticamente gli ostacoli alla sua realizzazione pratica.

Introduction

As concerns about climate change intensify, the concept of positive buildings has emerged as a vital architectural response. Positive buildings go beyond merely reducing their environmental footprint; they actively generate positive impacts on their surroundings and occupants. Regenerative design offers a holistic paradigm for creating buildings that not only minimize harm but also actively contribute to ecological restoration and community well-being. Architects play a pivotal role in mitigating environmental pollution through thoughtful design strategies during the early phases of a project. Passive strategies can harness natural forces for heating, cooling, and ventilation, thus reducing reliance on energy-intensive mechanical systems. Key design considerations include optimizing a building's geometry in accordance with climatic features and judiciously selecting materials to minimize adverse environmental effects.

This thesis investigates how architectural principles can enhance the capabilities of spatial structures to meet the objectives of positive buildings, with a particular focus on two specific passive design solutions. The first is an exploration of how building geometry contributes to environmental performance. The second examines the comparative impacts of aluminum and polycarbonate cladding systems, including their combined use. The subsequent chapters will explore these topics in greater detail. This research is divided into the following chapters to systematically examine the hypotheses and achieve the stated goals:

Chapter 1: Introduction and Foundation of Research

This chapter establishes the groundwork for the thesis. Following a brief introduction to the central research topic, the problem statement will be clearly articulated. Research questions and hypotheses will be presented, offering a focused direction for the investigation. Objectives will be derived from these hypotheses, ensuring a structured approach to the research. Finally, the chapter will outline the dissertation's innovative contributions and provide a roadmap for its overall organization.

Chapter 2: Literature Review

This chapter establishes a comprehensive understanding of the interdisciplinary knowledge underpinning the research topic. It will critically examine the latest scientific advancements in fields directly relevant to the design of positive buildings. This examination will encompass methodologies for climate-responsive design, structural optimization for positive architecture, sustainable material selection, the integration of recycled and upcycled materials, and other key factors contributing to practical goal

achievement. The chapter will culminate in a synthesis of these findings, establishing a robust theoretical framework to guide the subsequent research.

Chapter3: Research Methodology

This chapter details the methodology employed in the research, describing the research design, data collection methods, and analytical techniques used to address the research questions. It provides a thorough explanation of the choices made in the research process, including the selection of participants, materials, and instruments, as well as the procedures for data collection and analysis. The chapter also discusses the validity, reliability, and ethical considerations of the study, ensuring the research's rigor and integrity.

Chapter 4: Modelling and Analysis

This chapter presents a comprehensive explanation of the modeling and analysis procedures employed in the research. It thoroughly describes model development and simulation of relevant phenomena or systems, clarifying the theoretical foundations and assumptions upon which the models are built. The chapter details analytical methods used for interpreting model outputs, emphasizing their contributions to addressing the core research questions. Furthermore, it critically evaluates the models' accuracy and reliability, discussing validation techniques involving empirical data or relevant benchmarking criteria.

Chapter 5: Result, Interpretation, Conclusion, and Innovation

This chapter presents the interpretation of the findings from the modeling and analysis, drawing conclusions about the research questions and objectives. It discusses the implications of the results in the context of existing literature and theory, highlighting how the study advances understanding in the field. The chapter also identifies the innovative aspects of the research, outlining its contributions to knowledge and potential applications in practice. Finally, it reflects on the limitations of the study and suggests directions for future research.

This research includes five appendices, which are listed below. The appendices provide supplementary information that is relevant. They contain data and materials that support the research findings. Including these appendices ensures that the reader has access to all the necessary information to verify research methods and results without disrupting the flow of the research narrative.

Appendix 1: Research Experience in Boston

This appendix offers a detailed narrative and analysis of the research experience conducted in Boston. It clearly outlines the objectives for this period and describes the primary activities and achievements of the research undertaking. Collaborations, experiments, or focused studies conducted will be documented. Moreover, the chapter provides a critical reflection on the challenges encountered and the strategies employed to overcome them. A core focus will be the assessment of the Boston experience's impact on the thesis research itself, highlighting key learnings, skills gained, and how this period contributed to the researcher's professional development.

Appendix 2: Publications and Scholarly Outputs

This appendix highlights the researcher's scholarly contributions stemming from their thesis work. It presents a detailed overview of publications, including journal articles, conference papers, and other relevant scholarly outputs.

Appendix C: Comprehensive Diagram
This appendix encompasses all diagrams referenced within the text. Originally, limitations related to file format constraints precluded the inclusion of clearly formatted tables. To enhance clarity and facilitate a more thorough examination, all diagrams are presented here in an enlarged format, ensuring greater visibility and easier interpretation.

Appendix D: Comprehensive tables

This appendix includes all tables that are referred to within the main text of the thesis. Due to space constraints in the main document, these tables are presented here in full to ensure that comprehensive data is accessible for in-depth review and analysis. This arrangement allows the tables to be detailed and expansive, providing valuable context and supporting evidence for the research findings.

Flowcharts of thesis chapters:

Chapter 1: Introduction and Foundation of Research

Chapter 2: Literature Review

Chapter 3: Research Methodology, Strategy, Guidelines & Contribution in Boston research Experience

Chapter 4: Modeling and Analysis (Application of Tools)

Chapter 5: Interpretation of Results, Conclusion, and Innovation

Appendix A: Research Experience With TREND (Boston)

Appendix B: Publications and Scholarly outputs

Appendix C: Research Diagrams

Appendix D: Research Tables

CHAPTER 1
Introduction and foundation of research

1.1 Abstract

Climate change accentuates the need for architectural practices that go beyond zero-energy targets to achieve a net positive environmental impact. This research explores the pivotal role of spatial structures in the creation of positive buildings, with a focus on the selection of cladding materials and the influence of building geometry on environmental performance. While the impact of building operations on energy consumption is extensively documented, the contribution of structural components to achieving positive, and potentially regenerative, outcomes warrants further investigation. This chapter delves into the theoretical underpinnings of positive buildings, examining spatial structures, cladding systems, and regenerative design principles. It critically assesses the embodied energy and environmental impacts of various cladding materials, exploring how optimized building geometry can support the goals of positive buildings. Advanced modeling techniques will be employed to evaluate and synthesize empirical findings.
This chapter establishes the groundwork for the thesis. Following a brief introduction to the central research topic, the problem statement will be clearly articulated. Research questions and hypotheses will be presented, offering a focused direction for the investigation. Objectives will be derived from these hypotheses, ensuring a structured approach to the research. Finally, the chapter will outline the dissertation's innovative contributions and provide a roadmap for its overall organization.

1.2 State of the Problem:

This research seeks to address the urgent need to reduce the environmental impact of the building sector. To understand why this research path is crucial, the following key questions will be answered:

- Why this topic?
- Why Positive buildings?
- Why Regenerative Design?
- Why Spatial structures?
- Why Materials?
- Why Geometry?

1.2.1 Why this topic?

In recent years, the global escalation of environmental crises, including global warming, ozone depletion, and habitat destruction, has underscored the urgency for international commitments to mitigate human-induced environmental degradation. In 2023, unprecedented high temperatures were observed globally. In the absence of

effective climate action, the negative health impacts associated with climate change are anticipated to intensify, posing risks to billions of people worldwide (van Daalen et al. 2024). The building sector, as a major consumer of energy and natural resources, plays a crucial role in these impacts. For instance, European buildings account for approximately 50% of total energy use, 33% of water consumption, 50% of raw material extraction, and 40% of greenhouse gas emissions. In alignment with the UN Sustainable Development Goals (SDGs), achieving global and local sustainability targets requires focused attention on the construction industry to drastically reduce its energy demands and emissions. A substantial portion of a building's environmental impact occurs during its operational stage, typically comprising 60–90% of its lifecycle energy use and greenhouse gas emissions(Norouzi et al. 2022).

The building sector accounts for 30% of global final energy consumption (IEA, 2020) and nearly 50% of all resource extraction. It also generates large amounts of construction and demolition waste (CDW), equivalent to nearly 40% of annual extracted construction materials. The construction and operation phases contribute to 37% of greenhouse gas (GHG) emissions around the world, mainly from fossil fuel combustion for heat and carbon-intensive electricity consumption for appliances, lighting, and material production. Ongoing urbanization and population growth further emphasize the urgency of drastically decarbonizing the building sector to achieve the Paris Agreement goals. Emissions occur throughout a building's life cycle, with both operational (energy use) and embodied carbon (materials and construction) being important factors. While recent progress has been made in reducing operational carbon, minimizing embodied carbon is challenging and requires careful evaluation of strategies across all life cycle phases. Various modeling techniques, including building energy modeling (BEM), material flow analysis (MFA), and life cycle assessment (LCA) are used to evaluate decarbonization strategies within building stocks. Dynamic building stock models offer an integrated approach to consider the overall impacts of these strategies (Yang et al. 2022).

This growing trend of environmental pollution has established a critical and urgent responsibility for us as architects and engineers to address several key issues: reducing global warming and mitigating climate change, eliminating adverse environmental factors, reducing the excessive use of fossil fuels, reversing the decline in non-renewable resources, considering the economic consequences of neglecting energy of a project, paying attention to climatic factors in the design of large structures, and utilizing the embodied energy of materials efficiency management throughout the design, implementation, and operation phases.

Despite advances in modeling techniques, limitations persist in the comprehensive evaluation of decarbonization strategies for building stocks. These limitations include:

Siloed Approach to Strategies: Research often treats circular economy principles and energy transition in isolation, despite their interconnected nature in construction practices (Kullmann et al. 2021). Additionally, models frequently assume exogenous factors (e.g., technologies, policies, occupant behavior, climate) to be static, neglecting their dynamic interactions (IRP, 2020).

Inappropriate Scale: Prevalent top-down models provide insights into large-scale, long-term trends (Roca-Puigròs et al. 2020). This limits their ability to assess strategies that require localized focus or address building heterogeneity (Yang et al. 2022b).

Overlooked Material Decarbonization: The potential for decarbonizing materials (e.g., recycling, low-carbon production, bio-based materials) is often ignored (Zhong et al.,

2021). This is particularly problematic during renovations, where embodied emissions become proportionally more (Akbarnezhad and Xiao 2017).
Neglect of Lifestyle Impacts: While lifestyle changes can profoundly influence emissions, models primarily emphasize technical solutions. Lifestyle influences such as building usage intensity or altered temperature preferences need increased consideration in models (Pauliuk et al. 2021).

Therefore, to respond to the question 'Why this topic?' it can be answered in general. The building industry's massive carbon footprint, resource depletion, and contribution to environmental degradation demand immediate action. This research aims to explore innovative solutions that directly target these critical issues.

1.2.2 Why Positive Buildings?

In the face of the intensifying climate crisis and the widespread societal search for robust solutions to environmental challenges, several paradigms shape contemporary architectural and construction practices. Notably, effectiveness and ultra-efficiency have been dominant approaches. However, as societies grapple with rapid transformations and evolving sociocultural and demographic needs, our buildings must demonstrate a capacity for swift adaptation. This necessitates preparedness for change and the incorporation of strategies that facilitate the evolution of structures to accommodate diverse requirements over time.
Following the release of the 2013 IPCC report, the limitations of the efficiency paradigm in adequately addressing the climate crisis became starkly apparent within the scientific community and the broader public. This realization has driven a surge in research and exploration aimed at identifying more impactful solutions to environmental concerns. As succinctly articulated by Bryn Davidson, "We can't address climate change without thinking about buildings" (Figure 1.1).



Figure 1-1: The restore sustainability vision (Brown et al. 2018),

Contemporary architectural practice faces the complex challenge of integrating sustainability principles intrinsically, rather than relying on ad-hoc solutions applied late in the design process. This integration is inherently complex, requiring consideration of numerous criteria and interdisciplinary collaboration. While the concepts behind regenerative design have existed, translation of these principles into accessible frameworks and tools for architects remains a crucial need. The limitations of an energy efficiency-centric approach are evident; to meaningfully address biodiversity, air, and water quality, and achieve energy positivity, we must reimagine buildings as energy sources. This demands innovation in material use, aligning with

biological and technical cycles. A positive trajectory requires a fundamental shift in language, setting different goals that lead to novel designs and approaches. This shift, from a focus on ultra-efficiency to a paradigm of effectiveness, is necessary to enable the creation of truly positive built environments.
Consequently, in addressing the inquiry 'Why focus on positive buildings?' it can be articulated that the goal isn't merely to minimize harm but to create buildings that actively contribute to environmental restoration. Positive buildings offer a model for a future where the built environment generates more resources than it consumes.

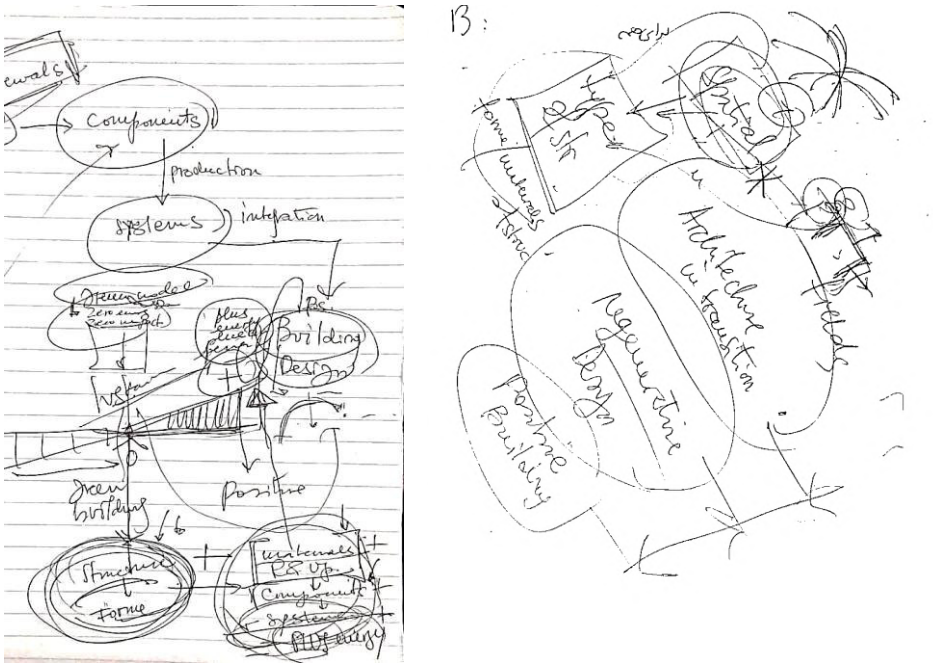


Figure 1-2: Critical Factors Identified in Early-Stage Proposal Analysis (May2022), Prof.C.Nava

1.2.3 why Regenerative design?

Architecture stands at the threshold of a transformative paradigm shift, moving beyond the conventional focus on resource linearity. Mitigating negative environmental impacts through increased efficiency has proven insufficient; addressing the climate crisis demands a fundamentally different approach focused on enhanced regenerative effectiveness. Over the next two decades, regenerative architecture will likely emerge as a dominant paradigm (Attiya 2018).
Regenerative design embodies processes that actively restore, replenish, or revitalize their source materials and systems. This creates a cyclical model where resource consumption is counterbalanced by the generation of outputs equivalent in quantity and quality. To design truly positive-impact buildings, architects must integrate complex constraints, ensuring that structures can replicate or regenerate their essential components and resources. A robust design framework is critical to facilitate informed decision-making throughout the design process.
The regenerative paradigm fosters anin-depth understanding of materials and embodied energy, promoting conscious selection of resources and countering reductionist design approaches. This shift holds the potential to create buildings with beneficial environmental footprints, aligning with the goals of the United Nations Framework Convention on Climate Change (Figure 1.3).

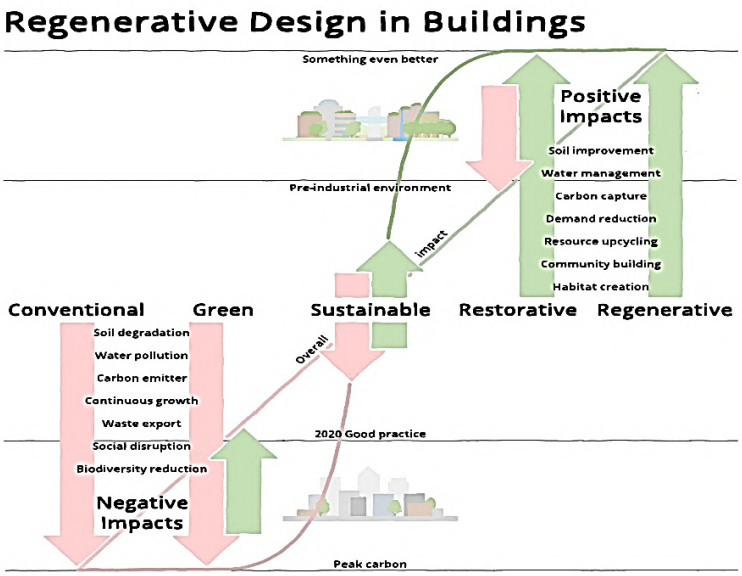


Figure 1-3: Architecture in transition (reference: International living future institute),

Therefore, to address the question of why regenerative design? it can be asserted that traditional sustainability approaches focus on minimizing harm, but they fall short of addressing the root causes of environmental degradation. Regenerative design offers a fundamentally different solution: it seeks to create buildings and systems that actively repair ecosystems, replenish resources, and foster a symbiotic relationship between the built environment and natural systems. This holistic approach aligns with the urgent need to not simply reduce our negative footprint, but to transition toward creating a positive impact on the planet.

1.2.4 Why spatial Structure?

Spatial structures hold significant promise in reducing environmental impact, particularly in large-scale projects. Their integration of innovative technologies, lightweight materials, prefabricated systems, and adherence to seismic safety standards demonstrates their potential for sustainable construction practices.

The inherent relationship between structure and architectural form in spatial structures highlights the necessity of structural knowledge for the comprehensive design process. Neglecting either structural principles or aesthetic considerations will impede the creation of successfully built environments. This interdependence is particularly critical when aiming for positive buildings, as the structural system directly influences a building's carbon footprint.

Parametric design capabilities and potential for prefabrication underscore the adaptability of spatial structures in facilitating the creation of "hybrid" buildings. Additionally, their inherent flexibility in form, material compatibility, and structural strength aligns well with climate-responsive design strategies and the goals of sustainable architecture. These characteristics, alongside the potential for energy optimization, make spatial structures compelling candidates for achieving positive buildings.

The realization of positive buildings, characterized by their active contribution to environmental well-being, demands an integrated design approach encompassing architecture, structure, and construction. Within the framework of regenerative design,

spatial structures offer a suitable platform for transitioning from a focus on ultra-efficiency to a paradigm of true effectiveness (Figure 1.4).

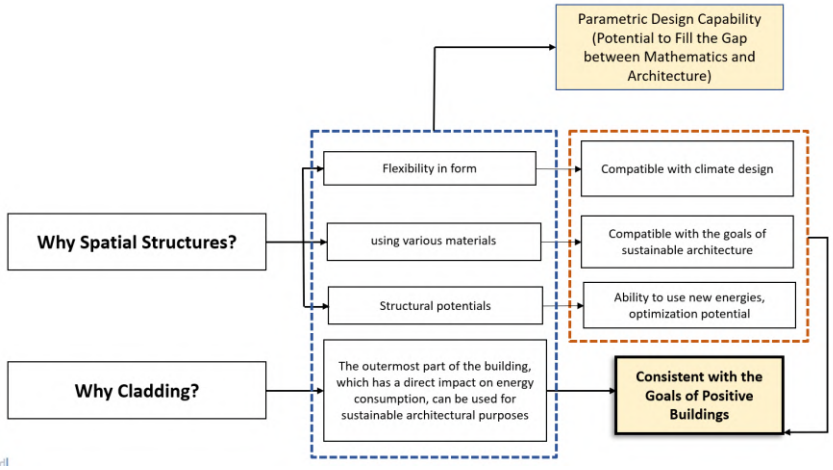


Figure 1-4: Spatial Structure and cladding s potential, (Reference: Author),

Therefore, to address the pivotal question 'Why spatial structures?', it is crucial to acknowledge their fundamental role in architectural design and their broader environmental advantages. The optimization of spatial structures not only dramatically reduces material consumption but also decreases environmental degradation. This approach is critical for advancing towards the goals of positive buildings, leveraging their inherent capacity to mitigate environmental impacts and promote ecological sustainability. By harnessing the environmentally friendly nature of spatial structures, we can advance their potential to move closer to achieving the goals of positive buildings, thereby making substantial strides towards sustainability and regeneration.

1.2.5 Why Materials?

The selection of materials and their associated cladding systems has profound and far-reaching consequences for the health of our planet. Research indicates that embodied carbon, which encompasses the emissions associated with material extraction, processing, transportation, and installation, can account for a significant portion of a building's total environmental footprint, some material impacts are:

Resource Depletion: The extraction and processing of raw materials, particularly non-renewables, drives deforestation, habitat loss, and the depletion of finite resources. This unsustainable practice compromises the well-being of future generations.
Pollution and Toxicity: Many conventional building materials release harmful pollutants throughout their lifecycle, contaminating air, water, and soil. These toxins pose significant risks to human health and ecosystems.
Climate Crisis Exacerbation: Energy-intensive material production and transportation generate massive greenhouse gas emissions, fueling the climate crisis and its associated extreme weather events, rising sea levels, and biodiversity loss.
Waste Generation: The construction and demolition sector is a major contributor to landfills, with materials often designed for obsolescence rather than longevity or circularity. This linear model perpetuates resource extraction and pollution cycles.

By focusing on materials and cladding as a "passive solution," we can make a profound difference. This approach entails a fundamental rethinking:
Embracing Regenerative Materials: Shifting towards bio-based, recycled, and low-embodied carbon materials supports responsible resource use and mitigates environmental harm.
Circular Design Principles: Designing for disassembly, adaptability, and reuse minimizes waste and extends the lifespan of valuable resources within the built environment.
Active Contributions: Exploring materials that sequester carbon, improve air quality, or support biodiversity demonstrates how buildings can become agents of positive environmental change.
Addressing the global environmental crisis demands that we urgently transform our approach to materials. This transformation is key to creating a built environment that not only minimizes harm but actively contributes to the regeneration of our planet.
Therefore, to address the question of why Materials? It can be asserted that Addressing material choices is therefore fundamental to achieving positive buildings and transitioning from paradigms of efficiency to regenerative effectiveness.

1.2.6 Why Geometry?

Geometry's importance in architectural design extends beyond traditional aesthetics and structural considerations to encompass a vital role in sustainable building practices. This expanded role is critical in addressing the contemporary challenges of resource conservation, environmental impact mitigation, and enhancing the well-being of building occupants. While geometry has been extensively investigated for its influence on energy efficiency in previous research, the broader environmental consequences and the impact of geometry on these factors remain areas requiring further exploration. In the realm of sustainable architecture, the strategic use of geometry facilitates the optimization of natural light, improves thermal efficiency, and reduces the environmental footprint of buildings. This research advocates for a systematic approach to understanding the nuanced impacts of various geometric configurations on a building's sustainability. It underscores the importance of integrating geometric considerations early in the design process to minimize environmental impact and optimize resource use.
The evolution of architectural practices has brought to the fore the concept of parametric design, where geometry plays a central role. Parametric design allows for the exploration of intricate geometric forms that are both aesthetically pleasing and environmentally responsive.
Geometry, when applied as a passive design solution, can play a critical role in the architectural design of positive buildings, exerting a substantial direct and indirect influence on their environmental outcomes. Fundamental geometric parameters such as the surface-to-volume ratio, building orientation, and architectural form, are instrumental in mitigating the ecological footprint of the built environment. These factors are essential in fostering enhanced environmental sustainability and resilience, thereby facilitating the development of structures that not only conform to but advance contemporary ecological standards.
An in-depth understanding of the relationship between geometry and sustainability is fundamental to developing such buildings. With the aid of advanced modeling and computational design, architects can utilize geometry to produce innovative, visually

appealing, and environmentally responsible structures. This holistic approach to sustainable design underlines the importance of geometry as a core component in crafting impactful and positive architectural solutions.
Therefore, to address the question of why Geometries? It can be asserted that the paper explores the role of geometry as a passive design element, stressing the necessity for sophisticated tools to model, calculate, and evaluate the environmental ramifications of a building's geometric characteristics. Employing advanced computational techniques enables the conception of dynamic architectural solutions tailored to specific environmental contexts, thereby bolstering the sustainability of buildings. The strategic application of geometry in architectural design highlights its crucial role in promoting environmentally sustainable and aesthetically pleasing built environments. This approach not only addresses ecological concerns but also contributes to creating more harmonious and integrated urban landscapes.

1.3 Research Objectives

To address the main topic of this research, two overarching goals have been established. These goals encompass the fundamental aims of the research and guide the exploration of solutions. At their core, these goals are:

1.3.1 General Goal 1:

Develop design strategies for spatial structure configurations that facilitate regenerative principles and achieve positive environmental impacts in buildings.

To comprehensively address the effect of the form in achieving positive buildings, general goal 1 is divided into two main goals. These goals strive to bridge the gap between theoretical understanding and practical application.

1.3.1.1 Main Goal 1-1:

Analyses the Impact of Geometric Forms on Building Performance in Specific Climates as a Passive Architectural Solution.

1.3.1.2 Main goal 1-2:

Developing design guidelines for optimizing geometric forms based on their environmental performance in specific climates.

1.3.2 General Goal 2:

To evaluate the effectiveness of various cladding systems as passive design solutions in enhancing the environmental performance of buildings and their capacity to meet LEED certification standards during the operational phase.

1.3.2.1 Main goal 2-1:

Quantitatively assess and compare the environmental impacts of aluminum and polycarbonate cladding systems on energy usage throughout a building's operational phase.

1.3.2.2 Main goal 2-2:

Optimize a hybrid cladding system to enhance its contribution to achieving LEED certification, compared to standalone aluminum and polycarbonate systems.

1.4 Research Questions

Research questions constitute the cornerstone of scholarly investigation, serving as a conduit for rigorous academic pursuit. They delineate the trajectory and concentrate on the inquiry, pinpointing the precise issues or domains the research intends to explore. These interrogatives steer the methodology for data gathering and analysis, guaranteeing that the study furnishes a substantive addition to the existing body of knowledge by probing into the extant lacunae. This study is poised to employ a meticulously formulated set of research questions to methodically examine the environmental ramifications of geometric configurations and cladding systems in architectural design.

To address the research objectives, the investigator formulated two overarching questions. Then to achieve the defined research goals, general questions should be systematically broken down into smaller, focused sub-questions. This hierarchical structure provides clarity and a practical framework for the research process. The outline of this approach is shown in the following:

General Questions: These are broad inquiries central to the research topic. They guide the overall direction of the investigation.

Main Questions: General questions are divided into two or more main questions, each exploring a specific aspect of the broader inquiry. This creates a more manageable scope for analysis.

Sub-questions: The main questions are further divided into practical sub-questions. These address specific details or tasks necessary to answer the main question and, ultimately, the overarching general question. Sub-questions provide a roadmap, ensuring the research stays focused and actionable.

With this framework for structuring research questions in place, the specific research question to be addressed in this study is defined as follows:

1.4.1 General Question 1:

How does the deliberate selection of geometric forms reduce the environmental impact of buildings?

This question has been divided into two main questions:

1.4.1.1 Main question 1.1:

How do different geometric configurations affect the environmental performance of buildings in a specific climate?

Sub-questions for Practical Application: To ascertain an appropriate methodology for addressing the primary research question, it was imperative to delineate specific, actionable questions. These practical inquiries have facilitated the researcher in identifying and selecting the most suitable methodological framework for the study. The practical questions are enumerated subsequently.

- How is it possible to assess the environmental impact of geometry?
- Which software can be used to investigate the environmental impact of geometry?
- The biggest impact of geometry on environmental consequences may be found in which category?

1.4.1.2 Main Question 1.2:

In building design, does changing geometric dimensions while maintaining equal volume result in a different environmental impact?

Sub-questions for Practical Application:

- How is it possible to assess the environmental impact of changing the dimensions of the Form?
- Which software can be used to investigate the environmental impact of changing the dimension of Forms a parametric variety?
- Which geometric dimension has the greatest influence on a building's environmental impact?

1.4.2 General Question 2:

How do various cladding systems impact the environmental performance of buildings and their compliance with the design principles of positive buildings during the operational phase?

This question has been bifurcated into two Main questions.

1.4.2.1 Main Question 2.1:

Considering the operational energy usage, which cladding system is more sustainable for buildings: aluminum or polycarbonate?

1.4.2.1.1 Sub-questions for Practical Application:

- What is the difference in energy consumption between aluminum and polycarbonate cladding systems?
- How do the environmental impacts of aluminum and polycarbonate cladding systems compare?
- Which cladding system is more likely to achieve LEED certification?

1.4.2.2 Main Question 2.2:

How does a combined cladding system model influence the environmental Impact of Buildings and sustainability?

1.4.2.2.1 Sub-questions for Practical Application:

- How does the hybrid system perform in terms of energy consumption for cooling, heating, and lighting compared to single-material systems?
- How do the hybrid cladding systems contribute to meeting LEED certification standards compared to standalone aluminum and polycarbonate systems?

1.5 Hypothesis

A hypothesis is a fundamental component of scientific research, representing a conjecture or proposed explanation made based on limited evidence as a starting point

for further investigation. It is a testable statement that predicts a possible outcome based on a set of conditions. The hypotheses corresponding to the overarching research questions are presented as follows.

1.5.1 Hypothesis 1:

In the climatic context of Boston, it is posited that buildings incorporating curved geometric forms will exhibit a statistically significant reduction in overall environmental impact, quantifiably measured by a reduced carbon footprint during the operational phase of the building's life cycle.

The Explanation of Hypothesis importance: In Boston Climate, investigating unconventional geometric forms with a focus on optimizing passive solar energy capture and minimizing heat loss has the potential to reveal design strategies that significantly reduce operational energy consumption compared to traditional rectilinear forms.

This hypothesis holds significant value for the advancement of sustainable building practices. By establishing a clear link between geometric form and energy use, the research can inform architects and designers about the potential for form optimization to contribute to energy-efficient buildings. This knowledge can be translated into design guidelines and best practices, ultimately leading to a reduction in the environmental impact of the built environment.

1.5.2 Hypothesis 2:

The strategic combination of cladding materials has the potential to significantly improve building sustainability during the operation period.

The Explanation of Hypothesis importance: The hypothesis that such combinations can significantly enhance sustainability holds substantial value for advancing environmentally responsible design practices. Cladding systems significantly impact a building's energy consumption and thermal behavior. However, their potential extends beyond these factors. By strategically combining materials with properties that address other sustainability aspects (e.g., recycled content, durability, end-of-life considerations), the research aims to inform design decisions that lead to a holistic reduction in a building's environmental footprint. Ultimately, the findings can contribute to the development of more sustainable buildings, minimizing the operational energy demand of the built environment.

The research goals, objectives, and hypothesis are summarized in the figures 1-5 & 1-6:

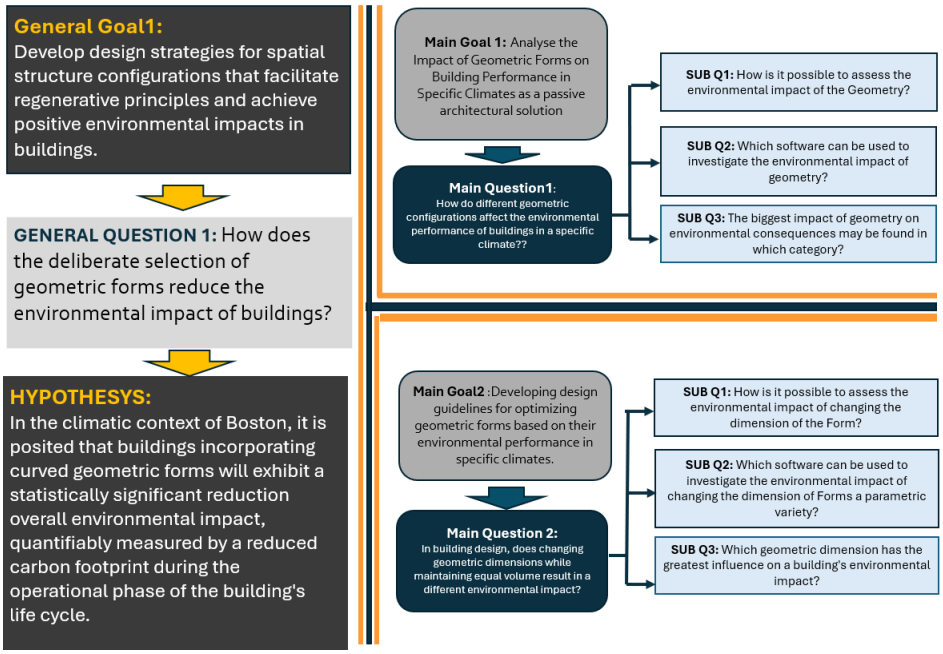


Figure 1-5: First Goal, questions, and hypothesis,) Reference: Author),

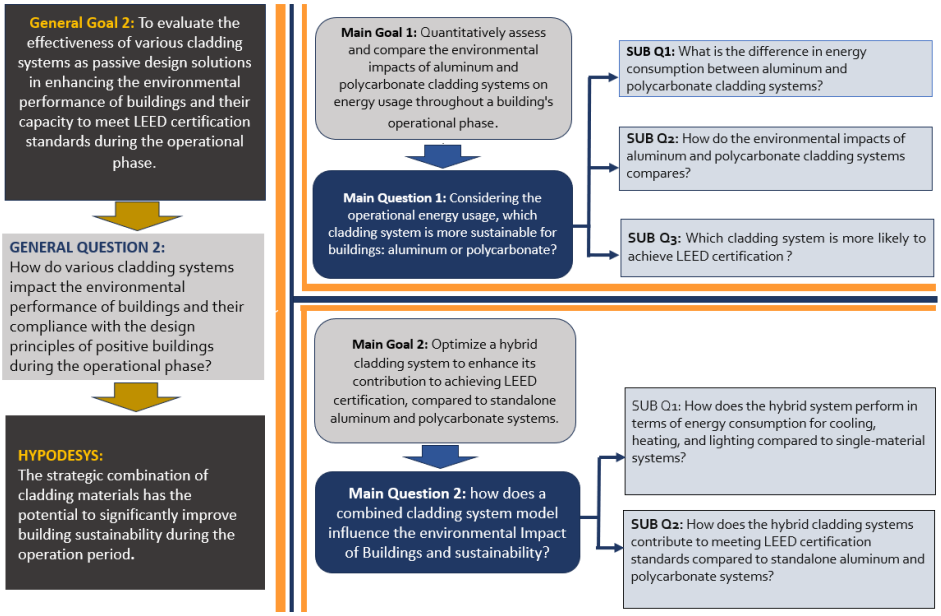


Figure 1-6: Second Goal, questions, and hypothesis, Reference: Author),

1.6 Research Methodology

The research methodology serves as the guiding framework that shapes the trajectory of this study, offering a systematic approach to uncovering insights and answering critical questions (Figure1.7).

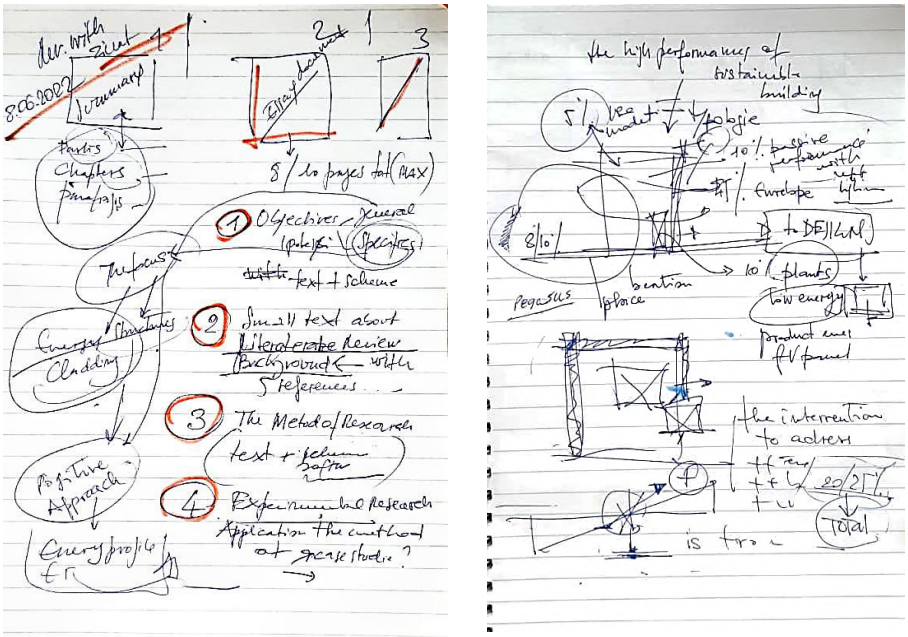


Figure 1-7: Research Structure, Jun 2022, Prof.C.Nava

It is through a well-defined methodology that the researcher navigates the vast landscape of knowledge, employing analytical, evaluative, and comparative techniques to unravel the complexities of the chosen topic. By delineating each step of the research process, from analytical description to comparative analysis, the methodology ensures rigor, coherence, and reliability in the study's findings. Moreover, it lays the foundation for comprehensive exploration, allowing for a nuanced understanding of spatial structures, claddings, positive buildings, regenerative design, and passive solutions. As such, the methodology stands as an indispensable tool, guiding the researcher towards meaningful discoveries and contributing to the advancement of knowledge in the field of positive buildings. In general, the research methodology is structured as follows:

1.6.1 Analytical Description (Defines and describes the proposed criteria to analyze the topic):

This phase involves defining and describing the criteria proposed for analyzing the topic. Analytical description will be conducted to identify and characterize spatial structures, claddings, positive buildings, regenerative design, and passive solutions. The section is executed in two steps: Step one involves searching for keywords on databases such as Scopus, Web of Science, and Google Scholar, reviewing articles, titles, and abstracts related to all sciences pertinent to the subject, and crafting the research inquiry, objectives, and hypotheses. Step two entails concluding the basics, principles, and characteristics of concepts related to the research axis. The outcome of this phase will be the writing of the Research Questions, Objectives, and Hypotheses, which will result in the preliminary research proposal.

1.6.2 Library Studying:

This part involves evaluating and examining previous studies and the most recent findings to gain a comprehensive understanding of the topic. It encompasses identifying potential problems, constraints, and obstacles encountered in achieving desired results, as well as understanding the potential and features of various components of the research. This section will be conducted in two steps. In the first step, the researcher will explore different scientific fields relevant to the research topic, such as climatic and bioclimatic design, sustainable buildings, positive buildings, material science in architecture, and the role of geometries in architecture. The goal of this literature review is to achieve the final achievements related to the research question. This phase involves both field and library research. In the second step, the researcher will engage in Methodological Exploration to Assess Diverse Research Approaches. Following the completion of the proposal, the researcher will define the Research Scope and Boundaries, establishing a Practical Framework. The result of this step will be Defining the Research Scope and Boundaries: Establishing a Practical Framework.

1.6.3 Comparative Analysis (Evaluating and Validating Research Findings):

This stage aims to verify, compare, and validate the findings of the research. Software modeling will be utilized to analyze the results and provide answers to the research questions by identifying and categorizing the effective factors. This part will be carried out in two steps: In the first step, modeling and analysis will be conducted. After analyzing the results and comparing and designing the diagram, the researcher will interpret the findings.

In the second section, the researcher, paying attention to the results, will answer the research questions. Finally, after organizing the research structure, the chapters will be written.
Diagram 1.1 shows a summary of general research methods.

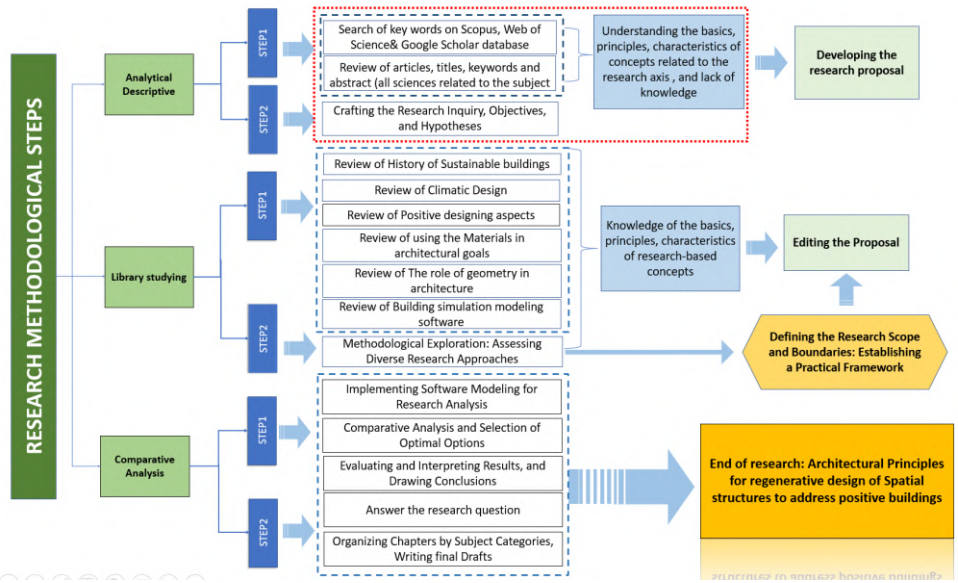


Diagram 1-1: A summary of General Research Method (Appendix C page 391)

CHAPTER 2
Literature Review

2.1 Abstract

A comprehensive literature review plays a pivotal role in any research endeavor. This chapter explores relevant books, theses, and international articles within fields related to the research topic. The primary goals of this review are to deepen understanding of the research problem, identify potential gaps in existing knowledge, and inform the selection of a suitable research methodology.

Given the interdisciplinary nature of this research, particularly the intersection of cladding systems within structural and architectural design, a thorough exploration of connected fields is vital. This process will create a robust foundation for addressing the research questions.

To achieve the study's practical goals, a comprehensive analysis of research in relevant scientific fields is indispensable. This chapter will examine scientific achievements in interconnected areas, culminating in a summary of the latest advancements in positive building design. The results will guide choices in methodology for regenerative design, climatic design, sustainable material selection (including recycled and upcycled materials), and other strategies to attain the desired research outcomes.

- The areas covered by this research are:
- A review of the Architecture paradigm in transition
- Climatic Design, Bio Climatic Design
- Sustainability, Sustainable architecture, Green Buildings
- Positive buildings, Zero Energy Buildings, Regenerative design, use of renewable energy
- Use of materials in Sustainable Architecture (Hybrid materials, Claddings, Sustainable materials, recycle and upcycle materials)
- The Role of Geometry in Architecture
- Energy simulation software and calculating the environmental effects of the building.

In the following, the latest research achievements in the mentioned fields will be investigated.

Web of Science, Scopus, and Google Scholar were searched for relevant articles.

2.2 Architectural paradigm in transition

The various architectural paradigms from 1908 to the present, such as Bioclimatic, Environmental, Energy Conscious, Sustainable, Green, Carbon Neutral, and Regenerative architectures, share a common theme of aligning building design with environmental concerns. In the evolution of architectural paradigms, a timeline from 1908 to the present day reveals significant shifts in design philosophies and practices. Between 1908 and 1940, Early Bioclimatic Architecture emerged under the influence of Richard Neutra, focusing on the utilization of local climate and environmental conditions, as exemplified by the Lovell Health House. The period from 1940 to 1970, marked by Mid-Century Modernism and Environmental Awareness, saw Frank Lloyd Wright's integration of modernist architecture with natural surroundings, with Fallingwater being a notable example. The Energy Crisis between 1970 and 1980 shifted focus towards energy efficiency and sustainable materials, highlighted by designs like The Solar House in response to the global energy crisis. The Green Architecture Movement from 1980 to 2000, led by figures like Ken Yeang, emphasized eco-friendly materials and low environmental impact, as seen in Menara Mesiniaga. The subsequent decade, 2000-2010, was defined by the rise of LEED Certification and Holistic Sustainability, with the U.S. Green Building Council playing a pivotal role and projects like the California Academy of Sciences by Renzo Piano exemplifying this trend. From 2010 onwards, the focus has shifted to Smart Green Design and Urban Sustainability, under the regenerative design movement, aiming to create buildings that contribute positively to the environment, a direction visible in projects like Terra - The Sustainability Pavilion for Expo 2020 Dubai. Currently, the architectural world is entering the realm of Regenerative Design, an advanced paradigm that seeks to restore and enhance ecosystems. This latest phase in architectural evolution emphasizes creating environmentally beneficial structures, marking a progressive shift towards building designs that are not only sustainable but also regenerative in their impact on the environment (Arslan and Ulubeyli 2023; Attia Shady 2018) (Baweja 2018)(Kannegiesser, Günther, and Autenrieb 2015)(Fox VERNON n.d.)(Wijesooriya and Brambilla 2021) Each paradigm, however, employs distinct approaches, solutions, and goals. The trajectory of architectural paradigms has been historically rooted in the discipline's response to environmental imperatives.

Table 2.1 presents a summary of the timeline of architectural paradigms. With the advent of the 2013 IPCC report, the limitations of the efficiency paradigm became evident, necessitating a shift towards more holistic and regenerative practices in the field of architecture (Attia Shady 2018).This shift reflects the broader discourse on sustainability that has significantly influenced architectural development over the last century, especially in the past three decades, prompting a re-evaluation of design methods to reduce environmental impacts through interdisciplinary strategies and innovative tools.

Paradigm	Years	Influencer	Key concept	Example
Early Bioclimatic Architecture	1908-1940	Richard Neutra	Utilization of local climate and environmental conditions to influence building design.	Lovell Health House (1929) by Richard Neutra
Mid-Century Modernism and Environmental Awareness	1940-1970	Frank Lloyd Wright	integration of modernist architecture with natural surroundings.	Fallingwater (1935) by Frank Lloyd Wright.
Energy Crisis and Sustainable Design	1970-1980	The global energy crisis, driving a focus on solar energy and efficiency	Energy efficiency and sustainable materials due to the energy crisis	The Solar House (1973) by University of Delaware
Green Architecture Movement	1980-2000	Ken Yeang, for pioneering bioclimatic skyscraper design	Eco-friendly materials, energy efficiency, and low environmental impact.	Menara Mesiniaga (1992) by Ken Yeang.
LEED Certification and Holistic Sustainability	2000-2010	U.S. Green Building Council, for establishing LEED certification.	Widespread adoption of LEED standards, focusing on holistic sustainable building practices.	California Academy of Sciences (2008) by Renzo Piano.
Smart Green Design and Urban Sustainability	2010-2016	The regenerative design movement, pushing beyond sustainability towards restoring and improving ecosystems.	Buildings that contribute positively to the environment, beyond sustainability.	The Sustainability Pavilion for Expo 2020 Dubai. By Grimshaw Architects.
Regenerative Design	2016 so far	Lyle, Braungart, Benyus	Restore, renew, or revitalize their own sources of energy and materials, creating sustainable designs that integrate with the natural environment	Bullitt Center in Seattle (2013), Washington by the Miller Hull

Table 2-1: summary of the timeline of architectural paradigms, combine refences [1],[2],[3],[4],[5],[6] with editing, (Appendix D, Page 443)

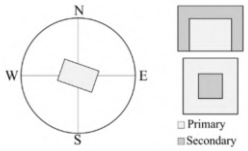
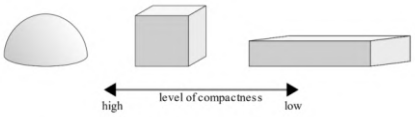
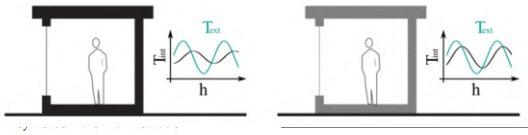
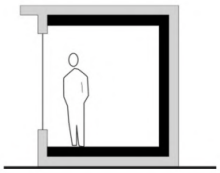
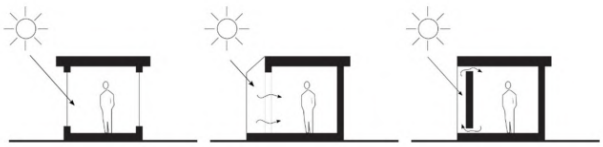
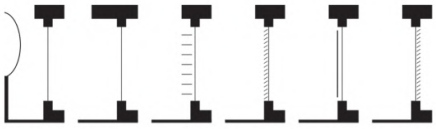
Guided by various paradigms concerning environmentally sustainable buildings, researchers have delved into distinct facets of such structures, including Net Zero Energy Buildings (NZEB), Positive Energy Buildings (PEB), and others. Each researcher has concentrated on specific aspects of these buildings, endeavoring to address the knowledge gaps and enhance understanding in this domain. Their work encompasses a broad spectrum of investigations, ranging from energy efficiency and renewable energy integration to occupant well-being and economic feasibility, all aimed at advancing the conceptual and practical frameworks of environmentally sustainable building design and operation.

With an awareness of the architectural transition and the various paradigms that have emerged along this trajectory, the ensuing section offers a detailed examination of studies concerning the definitions and practical applications for creating environmentally sustainable buildings. These investigations traverse a spectrum of design philosophies, encompassing bioclimatic architecture, sustainability, net-zero, and positive energy buildings. The goal is to establish a unifying framework for the evolving field of architecture, evaluate the effectiveness of different solutions, analyze how scientists have combined various approaches, and examine the integration of scientific advancements into diverse design strategies to lessen the environmental impact of buildings. The aim is to devise a comprehensive framework that precisely defines and guides the construction of positive energy buildings, aligning with the evolving paradigms of sustainable architectural practice.

2.3 Climatic Design, Bio Climatic Design

Climatic design, a subset of sustainable architecture, integrates the principles and criteria fundamental to creating environmentally responsive structures. This ideology emphasizes climatic approaches, particularly the adoption of passive solutions derived from traditional architectural practices, to address specific research questions. Historically, architectural firms have been profoundly influenced by their environmental contexts, exemplified by the construction of wooden structures in forested areas, stone buildings in mountainous regions, and adobe dwellings in desert landscapes. This adaptation illustrates the interplay between architecture as both a technical and artistic discipline, with the environment playing a pivotal role in shaping its evolution. This synergy between built forms and their environments is encapsulated in the concept of climatic architecture, achieved through strategic climatic design.
Climatic design, synonymous with bioclimatic design, entails a comprehensive set of scientific and practical principles. Adherence to these principles during the design process fosters the creation of spaces that are not only energy-efficient but also conducive to occupant comfort. Moreover, climatic design serves as a proactive measure in reducing a building's energy requirements for heating and cooling. It prioritizes the exploitation of natural energy resources to enhance indoor comfort levels, representing the foremost barrier against external environmental elements. The implementation of climatic design involves the integration of passive design strategies, the deployment of energy-efficient heating and cooling systems, and the promotion of energy-conscious behavior among occupants.
There is a lot of research being done in the field of climate design, and some of the recent works are listed below:

The increasing demand for cooling in buildings, driven by rising global temperatures associated with climate change, highlights the importance of passive design methods in architecture. Often referred to as "bioclimatic architecture strategies," passive design leverages the local environment to reduce reliance on active cooling measures, ensuring thermal comfort while minimizing energy consumption.
To address this topic within the Danish context, Bugenings and Kamri conducted a literature review Architecture Strategies in Denmark. Their study aimed to identify bioclimatic architecture strategies suitable for Denmark's unique climate. The paper systematically reviewed theoretical studies on common bioclimatic architecture approaches for the Danish climate and provided a comprehensive overview of 25 existing building projects in Denmark(Bugenings and Kamari 2022). Table 2.2 outlines the key passive strategies identified in their research.

Orientation and Space Zoning	 -
"Building massing", "building volume", "compactness"	
Thermal Mass	
Thermal Insulation	
Direct and Indirect Solar Gains	
Glazing	-
Sunspaces, also called winter gardens	-
Solar/Trombe Wall	-
Solar Shading, FLTR vegetation, overhang, fixed horizontal slats, external venetian blind, external screen and internal venetian blind	 -

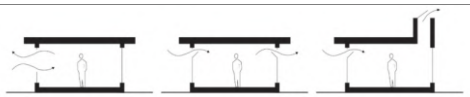
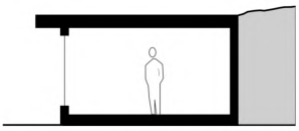
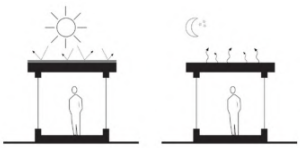
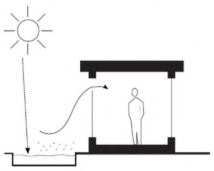
Convective Exchange	**Heat**	 Figure 8. Natural ventilation—single-sided ventilation (**left**), cross ventilation (**middle**) and stack ventilation (**right**).
Conductive Exchange	**Heat**	
Radiative Exchange	**Heat**	
Evaporative Exchange	**Heat**	

Table 2-4: Passive tactics, (Reference:(Bugenings and Kamari 2022)) with edit, (Appendix D, page 444)

In the realm of climatic design, the integration of traditional architectural principles into sustainable residential development is of paramount importance. The study conducted by Mohaibesh et al. exemplifies this approach, focusing on the application of vernacular design principles and material technologies to enhance the climate resilience of new structures. By employing the EDSL Tas simulation, their research assessed the thermal performance and energy efficiency of a proposed model against both traditional and contemporary residential buildings in various climatic zones. The investigation highlighted the role of thermal insulation combined with vernacular materials and design practices. Evaluation criteria included the physical attributes of the building envelope material, the overall design, window configurations, and building height, comparing these aspects in both new and historical constructions. These elements were pivotal in differentiating between traditional and modern residential designs. The findings of Mohaibesh et al.'s study underscored that the proposed building model exhibited superior climate resilience compared to modern residential structures, emphasizing the significance of traditional architectural knowledge in the evolution of sustainable and climate-adaptive housing solutions (Mohaibesh et al. 2021).

Exploring the provision of comfortable heating through climatic design is critical, given that the heating, cooling, and artificial ventilation mechanisms within buildings are substantial energy consumers. The 2017 study by Arindam Dutta and colleagues employed a validated Fortran 77 compiler program to explore the effect of building orientation on energy consumption. Their research focused on the thermal influx via windows in various orientations on vertical walls, within a tropical setting in the northern hemisphere.

The study revealed that south-facing windows incurred the highest heat gain, followed by east, west, and north-facing windows. To address this issue, the researchers introduced a novel solution: an experimentally constructed, movable external window shading device, synchronized with the sun's trajectory. This innovation was demonstrated in a tropical hospital building, where it effectively reduced the cooling

load, highlighting the importance of strategic building design and orientation in mitigating energy consumption in warm climates (Dutta, Samanta, and Neogi 2017).

In the context of solar shading control strategies, the comprehensive assessment of energy utilization alongside thermal and visual comfort is crucial. The work by Line Karlsen et al., which focused on developing a solar shading control strategy for Venetian blinds in office buildings situated in cold climates, exemplifies this approach. Their study aimed at achieving an optimal balance between energy consumption and indoor environmental quality. The analysis of annual performance outcomes suggested that the proposed control strategy could effectively mediate between energy efficiency and indoor environmental conditions, leading to satisfactory outcomes in both domains. This research underscores the importance of integrated evaluations in the design and implementation of solar shading controls, particularly in enhancing the sustainability and occupant comfort of office buildings in colder regions (Karlsen et al. 2016).

Understanding the effects of climate change on building heating and cooling requirements, alongside identifying cost-effective efficiency solutions and renewable energy sources, is fundamental in climatic design, given the strong influence of weather patterns on building energy needs. In a 2022 study by Kovelil Samuel et al., a prototype was developed specifically for regions with extremely warm climates, featuring innovative systems, bioclimatic architecture, and eco-responsive, sustainable strategies. This research introduces various advanced technologies and strategies to create comfortable living conditions and enhance building performance while reducing energy consumption. The approaches include utilizing bioclimatic architecture principles to decrease the cooling load and enhance natural light quality, incorporating user-centric controls that adapt to occupant activities. It discusses the 'Compensation law' in building design, which aims to reduce the energy demand throughout the day and night, and the 'Free Cooling' concept, which was tested in the prototype using outdoor temperatures to cool the building without mechanical ventilation when the weather is favorable. Additionally, the study explores the use of radiative sky cooling systems to utilize the night sky as a heat sink, thus decreasing the need for indoor cooling and energy consumption by chillers. The integration of photovoltaic panels into the building's design, including a dynamic roof pergola and vertical PV panels on the façade, is examined as a method to meet energy demands with renewable, clean energy, further enhanced by biomimetic solar cells. The research also highlights the importance of optimizing electricity and water usage through a smart monitoring system to maintain energy balance in the building (Kovelil Samuel et al. 2022).

To enhance thermal comfort and conserve energy through bioclimatic design principles, Elaouzy and El Fadar utilized Energy Plus software to investigate the impact of various bioclimatic design strategies in the Mediterranean region. Their study focused on five key strategies: window-to-wall ratio, solar heat gain coefficient, sun shading with overhangs, thermal insulation, and natural ventilation, assessing their influence on the energy consumption of an office building. Their findings suggest that in hot climates, strategies such as sun shading and the use of smaller glazed areas with low solar heat gain coefficients are effective in reducing energy demand. Conversely, in colder climates, larger glazed areas with higher solar heat gain coefficients are more beneficial. The research also highlighted the economic advantages of these design strategies, particularly emphasizing the significant benefits derived from thermal

insulation and natural ventilation in improving energy efficiency and reducing costs (Elaouzy and El Fadar 2022).

The study by Ozarisoya and Altan in 2021 aimed to evaluate the existing research on bioclimatic design systems, focusing on their potential to conserve global energy resources. Their work, which involved a systematic literature review, emphasized bioclimatic design elements within the context of the southern Mediterranean climate. This comprehensive evaluation proposed a hybrid approach to sustainability, deeply ingrained in the principles of vernacular environmental design. In their study, Ozarisoya and Altan methodically dissected the literature to outline the various stages of building energy simulations, demonstrating how these stages are integral to understanding and applying bioclimatic design principles. Their systematic approach not only highlighted the theoretical underpinnings and methodologies of bioclimatic design but also examined case studies to provide a practical perspective on implementing these principles in building designs. This approach served to bridge traditional environmental design methods with modern sustainability needs, offering a comprehensive view of how bioclimatic design can contribute to energy conservation on a global scale (Ozarisoy and Altan 2021).

Applying climatic principles in architectural design also involves selecting appropriate materials with consideration of the climate to increase the lifespan of buildings. Building durability, hygrothermal performance, and habitability are all significantly impacted by rainwater penetrating the façades of structures. Accurate hygrothermal simulations are essential for estimating the long-term performance of wall assemblies, where understanding the expected infiltration percentages through various external cladding surfaces is critical. However, predicting the exact amount of precipitation that will penetrate is challenging due to the stochastic nature of rainwater penetration through these assemblies. Van Linden and colleagues conducted a review of quantitative studies on infiltration rates, which were predominantly laboratory-based. Through these studies, the primary drivers for infiltration were identified, and the influence of various factors, such as the testing method employed, the pressure differential, and the rate of water deposition, on infiltration rates was analysed. This research led to the classification of cladding materials and the development of a methodology for assessing penetration percentages without the need for additional laboratory experiments. This approach enables more informed decisions in material selection, enhancing the durability and climate resilience of building designs. (Van Linden and Van Den Bossche 2022). Pérez-Bella et al., conducted a study to characterize the directional exposure of Mexican façades to rainwater penetration, focusing on wind-driven rain (WDR) and driving rain wind pressure (DRWP) across the country. A significant aspect of this work is the development of a methodology for calculating the amount of rainfall impacting the façade, considering the angle of incidence and the wind direction against the building's façade. This method is crucial for understanding how climate influences architectural design and construction decisions. By clarifying the effect of climate, particularly the interaction between wind and rain on building façades, the study provides valuable insights for architects and builders to design and construct buildings that are better adapted to their local environmental conditions, enhancing their resilience to weather-related challenges(Pérez-Bella et al. 2022).

The studies make it clear that the building envelope plays a vital role in enhancing energy efficiency, maintaining thermal comfort, and facilitating climatic adaptation of

structures. Arash Pourghorban et al., explored various configurations and key environmental factors, such as climatic context and orientation, in their research on the performance of reflective insulation systems (RISs). This examination was particularly important given the significant impact of environmental conditions on the effectiveness of RISs. Through the application of new and verified calculation models and analytical methods, the study assessed the interior heating/cooling demands and energy consumption metrics. The findings revealed the dynamic performance of RISs, showcasing their substantial potential to reduce cooling energy consumption by up to 12.48 MJ/m^2. The study also noted that orientation could lead to an 11.40% variation in relative consumption differences across different climates, indicating the sensitivity of energy performance to building orientation. Moreover, RISs were found to be generally more effective in reducing energy consumption values by 42.34%, compared to their impact on enhancing thermal comfort levels, which stood at 28.21%. This emphasizes the importance of considering reflective insulation systems in the architectural design process for their significant contribution to lowering energy usage and supporting the climatic adaptation of buildings (Pourghorban, Kari, and Asoodeh 2022).

In addressing climate-responsive design, the emphasis on passive strategies for achieving comfortable conditions highlights their efficacy as positive solutions. Passive heating, which involves heat retention and admission, and passive cooling, focusing on heat exclusion and heat dissipation, are central to bioclimatic environmental design. In their 2022 study, Bugenings and Kamari introduced and detailed various strategies related to bioclimatic architecture, specifically emphasizing passive cooling and passive heating approaches. These strategies are integral to designing buildings that naturally maintain comfortable temperatures, reducing the need for mechanical heating and cooling systems. For instance, passive cooling might involve architectural features like shading devices, natural ventilation, and thermal mass to keep indoor spaces cool, while passive heating could leverage solar gain and insulation to warm up interiors. Figure 2.1 provides a comprehensive overview of these passive cooling and heating strategies, illustrating how different techniques can be implemented to enhance the thermal comfort and energy efficiency of buildings in alignment with their climatic context (Bugenings and Kamari 2022).

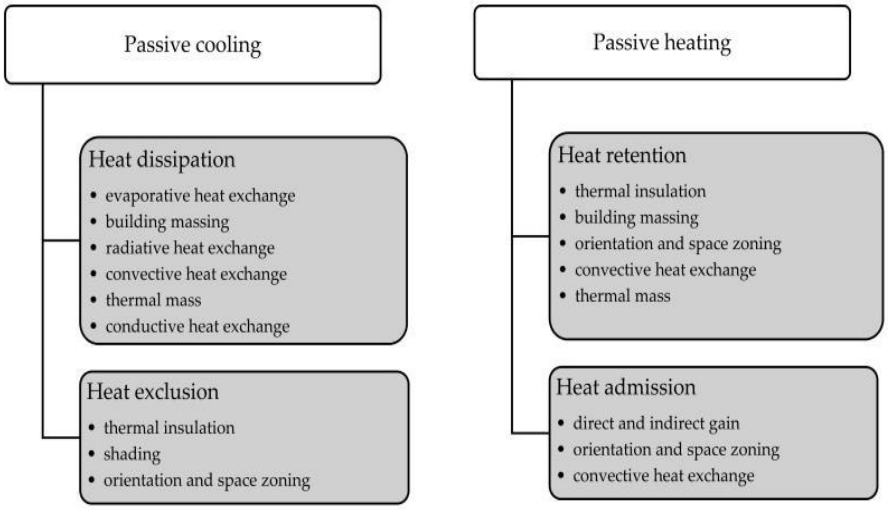


Figure 2-2: Bioclimatic architecture strategies-passive cooling and passive heating (reference: Bugenings and Kamari 2022),

The building thermal mass concept is pivotal in bridging the gap between renewable energy supply and demand, serving as a natural energy storage system that modulates loads. Yan Ding and his team crafted a reduced-order RC model to assess the cooling and heating demands of buildings, thereby defining a metric termed "effective thermal capacitance" to evaluate the thermal mass of buildings. In their study focusing on typical houses in the Peruvian Meso Andean region, they investigated the direct correlation between effective thermal capacitance and building sizes. By employing the particle swarm optimization algorithm, they calculated the effective thermal capacitance values. Their research led to the recommendation of various passive design strategies aimed at enhancing thermal comfort tailored to these dwellings, taking into account the local climate and architectural practices. This methodology highlights the importance of incorporating passive design elements and leveraging building thermal mass to improve energy efficiency and comfort in residential structures within the specific environmental conditions of the Meso Andean area in Peru (Resano, Rodriguez, and Guillen 2022).

Summary :

Climatic design is crucial for achieving optimal energy efficiency in architecture. Known as building bioclimatic, this field integrates a comprehensive set of scientific and pragmatic principles into the design process, leading to spaces that excel in comfort and energy efficiency. The primary challenge in climatic design is to meet contemporary needs, which have evolved significantly from the past. The aim is to reduce energy consumption and use environmentally friendly materials while considering the building's location and interior layout.

The core objectives of climatic design, as identified in scholarly literature, include reducing energy consumption and waste, mitigating wind-induced energy loss, utilizing sunlight for heating, protecting against adverse external air conditions, exploiting diurnal temperature variations, using beneficial external air, providing sun protection, managing internal blinds, optimizing humidity, and safeguarding against precipitation, dust, and noise pollution.

Aligned with the bioclimatic design approach for 'positive buildings,' the design process should exploit climatic potentials through form, orientation, material selection, insulation, and integration of vegetation. These elements promote a design that is both bioclimatically aligned and harmoniously integrated with its climatic setting. Enhancing climatic design involves:
Natural Ventilation: Analysing prevailing wind patterns to optimize natural ventilation and protect against unwanted wind effects. Encouraging airflow through strategically placed openings for building cooling and healthy indoor air quality.
Strategic Orientation: Positioning the building to take advantage of favorable sun and wind patterns for passive heating, cooling, and ventilation.

- Shading Devices: Using external shading (overhangs, louvers, vegetation) to control solar gain and reduce internal heat.
- Material Selection: Choosing materials with suitable thermal properties for the climate, like high thermal mass materials in regions with significant temperature variations, or reflective materials in hot climates.
- Landscaping: Using vegetation to provide shade, moderate wind, and enhance the microclimate.
- Thermal Mass: Employing materials that can store heat or coolness, aiding in indoor temperature stabilization.
- Daylighting: Maximizing natural light to decrease the need for artificial lighting.
- Adaptive Design: Creating flexible spaces for comfort in varying climate conditions.

This strategy not only promotes thermal comfort and energy savings but also aligns with sustainable and environmentally responsive building practices.

2.4 Sustainability, Sustainable Architecture, Green buildings

The integration of sustainability principles and the objectives of sustainable development to minimize energy dissipation and environmental contamination has given rise to the concept known as "sustainable architecture." This architectural paradigm ensures that buildings are not only climatically responsive to their local environments but also engage in a symbiotic interaction with them. The World Commission on Environment and Development articulates sustainability as a mode of development that fulfills current needs without compromising the ability of future generations to meet their own requirements.
Transitioning from the technological and environmental assessments of sustainable energy and building practices, the concept of "sustainable architecture" often presents itself as an ambiguous term within the architectural discourse. The phrase, perceived as all-encompassing yet undefined, reflects the expanding scope of sustainability within the architectural vernacular. Elizabeth Donovan's research delves into this nebulous domain, aiming to elucidate the meaning of sustainable architecture through a series of studies. Her work critically examines the linguistic challenges surrounding sustainable architecture, scrutinizing its definitions in literature and research, and contemplating the implications for the architectural profession. Drawing on the influential Brundtland report and the Sustainable Development Goals (SDGs), Donovan's findings advocate for a refined and expansive lexicon that can facilitate a more integrated approach to sustainability across various professions, particularly in

response to the global climate crisis. This endeavor highlights the prominence of the Brundtland Commission's definition of sustainable development and the illustrative Venn diagram of sustainability's three pillars, offering a clearer framework within the architectural field (Donovan 2020). The Brundtland Commission's definition of sustainable development, articulated in the 1987 report "Our Common Future," is: "Sustainable development is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs." This definition emphasizes the importance of balancing economic growth, environmental protection, and social equity to ensure that current and future generations can enjoy a healthy and productive life.

Central to the concept of sustainable architecture are the three pillars identified by the United Nations Brundtland Commission—economic, environmental, and social sustainability—which were later reinforced by the 2030 Agenda for Sustainable Development and its associated goals (Michelle E.Jarvie 1987) (Figure2.2).

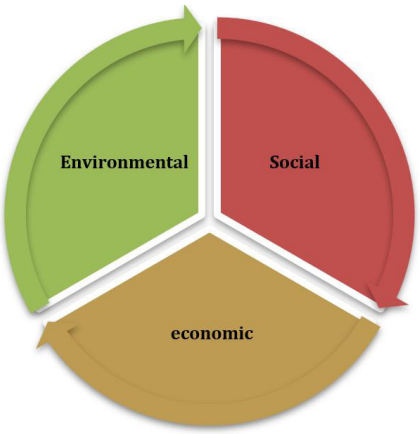


Figure 2-5: Tree pilar of sustainability,(Allen 2022)

Sustainable architecture necessitates environmental consciousness, with its efficacy intrinsically connected to how it interacts with and presents itself within the environment. This architectural domain, like others, is governed by distinct principles and guidelines, encapsulating three core phases: resource conservation, design for lifecycle integration, and human-centric design. Each phase encompasses specific strategies aimed at fulfilling the overarching sustainable agenda.

For a building to be deemed sustainable, it must adhere to several key principles, including energy conservation, climatic harmony, reduction in non-renewable resource usage, fulfillment of occupant needs, site interaction, and a holistic approach to design and functionality.

Understanding the importance of design decisions is paramount in addressing the sustainability of buildings, as these choices significantly influence their energy and environmental performance. A systematic approach for design decision support is notably lacking, which is essential for tailoring decisions to the unique design parameters of each project. The investigation by Mumine Gercek and Zeynep Durmuş Arsan into residential building design in Turkey exemplifies this, focusing on the analysis of annual energy consumption and operational CO_2 emissions under current and projected climatic conditions. Their findings highlight that the solar heat gain coefficients (SHGC) and heat transfer coefficients (U) of transparent surfaces on building envelopes critically impact the energy and environmental efficiency of residential buildings in hot-humid climates. This research underlines the need for a

strategic approach in design decisions to enhance the sustainability and performance of buildings (Gercek and Durmuş Arsan 2019).

Transitioning from individual building design to broader urban development, the construction sector's extensive resource usage and energy consumption come to the forefront. With an urban population projected to reach 6.5 billion by 2050, the adoption of sustainable construction practices becomes imperative. These practices, however, demand a significant methodological overhaul in urban development and maintenance. The study by McNeil-Ayuk and Jrade introduces an innovative model that integrates Building Information Modeling (BIM) with sustainability principles at the early design stages of buildings. This model facilitates the automated evaluation and selection of construction technologies, encompassing conventional, modular, and 3D printing methods, and allows for an early assessment of design alternatives to identify the most appropriate construction technique. Incorporating modules like Lifecycle Assessment (LCA), Lifecycle Cost Analysis (LCCA), Energy Analysis (EA), and Sustainability Certification (LEED), the model seeks to transform the conceptual design phase, paving the way for more sustainable urban development (McNeil-Ayuk and Jrade 2023).

Building on the integration of Building Information Modelling (BIM) and sustainability in urban development, Implementing a new optimization strategy based on topological optimization, facilitated by recent digital advancements, along with innovative manufacturing technologies and materials research, fosters sustainable growth in design and construction. Modern design requires a multidisciplinary approach, necessitating architects to collaborate across fields such as construction, material engineering, and fabrication technologies, and to optimize design, manufacturing, and energy use processes. Drawing inspiration from nature, contemporary design practices offer unique opportunities to create complex, mold-free shapes while adhering to sustainable development principles. Saurav Dixit and Anna Stefanska (2023) examined the role of biomimicry in shaping architectural and structural designs of the twentieth and twenty-first centuries, highlighting nature's geometrical patterns as valuable resources for architects and engineers. Their findings underline the importance of integrating bio-logic principles into a comprehensive, multidisciplinary design process to advance sustainable and innovative architectural practices (Dixit and Stefańska 2022).

The pursuit of environmentally sustainable buildings has led researchers to explore various positive solutions, with a significant focus on the integration of lighting and electricity generation. Advances in these areas have been crucial in enhancing safety and performance, both indoors and outdoors, contributing significantly to sustainability objectives. This theme is prevalent among studies examining the impact of buildings on climate change. Berta Garcia and Osama's research in Alexandria, Egypt, showcases an innovative daylight utilization system within a public library, aligning with the zero-energy building concept. Their study presents three strategies to boost energy efficiency: the integration of photovoltaic (PV) systems to replace conventional lighting, the adoption of nanomaterials in construction, and the implementation of a unique anabolic lighting system to control daylight exposure. By optimizing solar energy through a vertical lighting design, the project demonstrates how targeted modifications can enhance environmental sustainability and health, offering a progressive model for sustainable architectural design (Garcia-Fernandez and Omar 2022).

Sustainability encompasses more than just reducing energy consumption. The International Energy Agency (IEA) underlines energy efficiency's role in securing a low-carbon future and its health and well-being advantages. Yet, energy efficiency efforts can compromise indoor environmental quality (IEQ) if not properly implemented. The passive house concept's performance, especially in energy use and thermal features, has been extensively studied. However, there is a gap in the design phase regarding a dynamic method for predicting thermal comfort to evaluate design effectiveness. Alhindawi, Ibrahim, and Jimenez-Bescos in 2022 investigated a computational method to forecast thermal comfort levels under peak summer conditions in a UK Passive House, emphasizing the importance of natural ventilation for adequate airflow. This method integrates EnergyPlus dynamic simulations, ANSYS computational fluid dynamics simulations, and the Centre for the Built Environment Thermal Comfort Tool, providing insights into the natural ventilation's role in maintaining comfortable and sustainable indoor environments (Alhindawi and Jimenez-Bescos 2022) .

Building on the importance of sustainability in design and construction, China's significant environmental challenges have catalyzed research into mitigating pollution, especially in the construction sector. Energy-efficient university campuses are crucial for sustainable urban development and achieving China's carbon neutrality goals. The diversity of buildings on university campuses necessitates standardized evaluation methods. In this context, Liu and Wang's study emphasizes the significance of Building Information Modeling (BIM) technology in green building design and construction, particularly for university buildings in northern China. Their research enhances green performance in areas such as the surrounding environment, functional layout, envelope performance, system transformation, and management methods. They developed a Green BIM-based approach to analyze building performance, applied to typical university buildings in northern China. The optimization achieved substantial annual load reductions of about 47.4%, complying with national energy efficiency standards for public buildings, with heating and cooling loads reduced by 59.1% and 21.5%, respectively (Liu and Wang 2022).

Continuing the discussion on sustainable building practices, green roofs, and photovoltaic panels are increasingly explored as solutions for zero-energy buildings and mitigating urban heat islands (UHIs). These features are essential in developing eco-friendly urban environments. Mohamed E. Abdalazeem and colleagues conducted a comprehensive review in 2022, examining the impact of green roofs (GR) and integrated photovoltaic-green roof systems (PV/GR) on UHI mitigation, energy savings, and indoor thermal comfort in urban buildings. Analyzing 157 papers from the Scopus database, they found that both GR and GR/PV systems significantly enhance building performance in hot, arid climates, especially for larger structures. This study underscores the potential of integrating green roofs and photovoltaic panels in urban design to achieve sustainable and energy-efficient buildings (Abdalazeem et al. 2022).

Building on the exploration of integrated solutions for sustainable urban development, attention also turns to passive strategies like thermal insulation in building design. Thermal insulation, particularly through pre-formed interior panels imbued with phase change materials (PCMs), can significantly bolster the thermal resistance and capacitance of building envelopes. This enhancement not only improves energy performance but also increases the building's energy flexibility, facilitating its participation in demand-side management and demand response programs. However, the literature reveals a gap in studies focusing on energy flexibility and demand response, especially in designs that incorporate PCMs within the building envelope. The

research by Saffari, Roe, and Finn in 2022 delves into the impact of PCM-impregnated building envelopes on thermal performance and the building's energy characteristics under different demand response scenarios. Their findings underscore that envelopes enhanced with PCMs are highly effective in shifting cooling demand and improving energy flexibility, thus presenting a valuable contribution to sustainable building practices (Saffari, Roe, and Finn 2022).

Sustainability is not limited to new constructions; indeed, existing buildings are significant sources of environmental pollution. Transitioning to sustainable cities necessitates rehabilitating, retrofitting, and refurbishing these buildings to decrease energy consumption and mitigate global warming impacts. Implementing multi-layer interior insulation serves as an effective strategy to transform existing structures into nearly zero-energy buildings (NZEB), offering a cost-efficient route to energy reduction. The diversity in building envelope products necessitates careful consideration of their environmental impacts. In this context, Nima Amani and Ehsan Kiyaee's 2020 research contributes valuable insights by developing a two-criteria framework for assessing thermal insulation materials for building cladding. Their approach, which employs a four-layer insulation system using twelve different insulation materials, aims to optimize the balance between energy efficiency and environmental impact, underlining the critical role of strategic material selection in enhancing the sustainability of existing buildings (Amani and Kiaee 2020a).

Building on the strategic material selection for sustainability in existing buildings, attention also turns to the challenge of identifying sustainable energy solutions for remote rural electrification. The determination of the most sustainable small-scale off-grid renewable energy systems, especially for remote communities, is complex due to the myriad of technologies and configurations available. Jhud Mikhail Aberilla and colleagues addressed this complexity by evaluating the environmental sustainability of energy systems that combine diesel, solar, and wind energy with battery storage for residential and community use. Their research concluded that the optimal solution is a system that integrates household-scale photovoltaic (PV) panels, community-scale wind turbines, and lithium-ion (Li-ion) batteries within a microgrid framework, thus identifying a path toward environmentally sustainable energy provision in isolated areas (Aberilla et al. 2020).

Seeking sustainable energy solutions for remote locations aligns with advancements in building-integrated technologies, such as transparent photovoltaics (TPV). With the dual function of energy generation and conservation, TPV holds promise for applications like windows and skylights. Annick Anctil et al. investigated the potential of TPV across four diverse US cities (Detroit, Los Angeles, Phoenix, and Honolulu). Their study employed building energy demand modeling, photovoltaic generation assessments, and life cycle analysis (LCA), finding a positive net energy benefit (NEB) across all locations. This result underscores the low cradle-to-grave energy footprint of transparent organic photovoltaic modules. Further, their analysis of energy return on investment (EROI) and energy payback time (EPBT) emphasizes the environmental and economic benefits of TPV integration within the US, specifically for its potential to reduce building energy demands while generating on-site power (Anctil, Lee, and Lunt 2020).

Balancing environmental and structural requirements in building design is crucial for sustainable development. The EFIResources project focuses on developing a performance-based approach to sustainable design, aiming to harmonize environmental and structural criteria. This approach facilitates the assessment of

resource efficiency early in the design process, aligning with European policies on resource efficiency in construction. By integrating environmental criteria into the decision-making process, structural engineers can promote resource efficiency and reduce the environmental impacts of construction, setting a benchmark for the life-cycle performance of building structures (Gervasio and Dimova 2018).

Summary :

Advancements in sustainable building practices have significantly reduced environmental footprints and enhanced resource efficiency, with innovations in materials, construction methods, and design principles leading to energy-efficient and health-promoting buildings. These developments have facilitated the conservation of natural resources, minimized waste and emissions, and fostered a harmonious balance between human habitation and the natural environment. This progress marks substantial achievements in sustainable development within the construction industry. However, while scientists strive to find solutions to decrease environmental impacts, merely focusing on reducing these impacts is insufficient. Current paradigms like zero energy buildings, though beneficial, do not fully address the broader climatic challenges.

The pursuit of sustainability requires innovative, cross-disciplinary solutions that go beyond conventional approaches to significantly mitigate the environmental consequences of construction. Sustainable design principles such as energy, water, land, and material efficiency, along with reduced maintenance costs and environmentally friendly architecture, are critical. Yet, the limitation lies in the existing paradigm's ability to confront climatic issues comprehensively. Therefore, the next section will explore the transition from current paradigms to newer ones, detailing new achievements, methods, and approaches in sustainable building design that better address these complex environmental challenges.

2.5 Positive buildings and Regenerative Design

The evolution of architecture post-industrial revolution is characterized by a bifurcation into two main paradigms: Efficiency and Regenerative. The Efficiency Paradigm, encompassing approaches like Bioclimatic, Environmental, and Green Architecture, has focused primarily on minimizing the negative environmental impacts of construction. However, the burgeoning awareness of climate change has propelled a transition towards a Regenerative Paradigm, which aims to restore and enhance ecosystems (Attia Shady 2018) This paradigm, projected to dominate the forthcoming decades, draws from the pioneering principles of Lyle's regenerative design, Braungart and McDonough's cradle-to-cradle model(Braungert 2018) (Anon n.d.-b), and Benyus's principles of biomimicry (Benyus 2002)

This sustainable approach demands an integrative process that spans resource conservation, life cycle design, and human-centric planning, supported by modern methodologies such as building information modelling and topological optimization in conjunction with new materials and manufacturing technologies (Dixit and Stefańska 2022). The late 20th century marked a pivotal advancement in eco-design, led by advocates like Bob Berkebile and his push for eco-friendly practices within the

American Institute of Architects. This era saw the confluence of architecture with the biomimicry-material science and bionics, where the emulation of biological systems has fostered technological solutions aimed at reducing ecological footprints (Elmoghazy and Afify 2020) (Gruber n.d.). Such interdisciplinary approaches have solidified the adoption of nature-based, nature-derived, and nature-inspired methodologies, effectively ushering in a paradigmatic shift towards designs that not only coexist with but regenerate the natural environment (Palombini et al. 2016).In this context, Shady (2018) posits that buildings of the future should serve as material banks, where resources are preserved within biological and technical cycles, thereby facilitating the development of circular and regenerative buildings. This progressive paradigm champions the principles of cradle-to-cradle (C2C), emphasizing material health, reuse, and renewable energy, all under the umbrella of social fairness, providing architects with a framework to design structures that positively impact both people and the planet within the current capitalist framework. Figure 2.3 shows the Paradigm shift towards a beneficial positive impact footprint of the built environment.

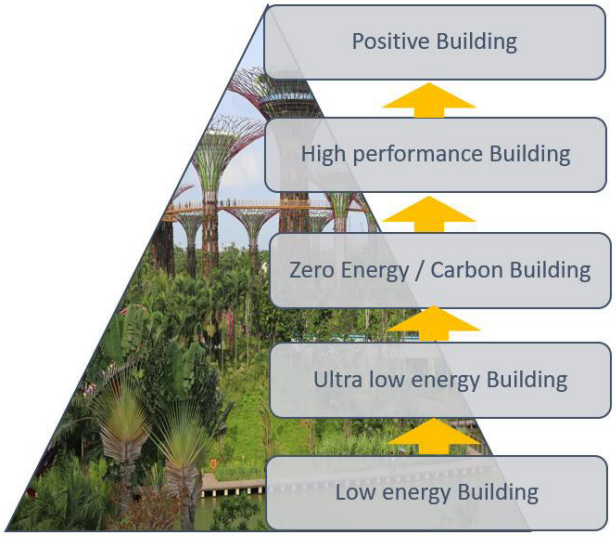


Figure 2-8: Paradigm shift towards a beneficial positive impact footprint of the built environment,(Attia 2016) with edition by Author

The regenerative architecture paradigm thus represents a critical and necessary evolution in architectural thought, signalling a move away from myopic resource efficiency to a broader, more impactful ecological engagement with the built environment. Table 2.3 delineates how various architectural ideologies—specifically Bioclimatic, Environmental, and Energy-conscious architecture—align with the principles of reducing environmental impact and enhancing effectiveness in sustainable design. It classifies these ideologies under approaches like Discovery, Harmony, and Energy Efficiency and evaluates their effectiveness in areas such as Resource Efficiency, Neutrality, Resiliency, and Recovery. Nature-derived ideologies show a comprehensive approach, aligning with all paradigms and effectiveness criteria, while Nature-inspired and Nature-Based selectively contribute to environmental recovery and resiliency(Ahmed and Rasul 2023; iZCi 2022; Manzano-Agugliaro et al. 2015) (Kent 2023).

Table 2-7: categories of paradigms base on Nature solution approaches (Reference: Author), Appendix D, Page445

Paradigms	Decrease Negative Impact by					Effectiveness	
Approach	Discovery	Harmony	Energy efficiency	Resource efficiency	Neutrality	Resiliency	Recovery
Ideology	Bioclimatic architecture	Environmental architecture	Energy conscious architecture	sustainable architecture	Green architecture	carbon neutral architecture or High performance	Regenerative architecture
Nature-derived	*	*	*	*	*	*	*
Nature-inspired	-	-	-	-	*	*	*
Nature-Based	-	-	-	-	-	-	*

John Tillman Lyle is considered a significant influencer in the field of regenerative design. His work, notably the book "Regenerative Design for Sustainable Development" published in 1994, was instrumental in defining the principles and methodologies of regenerative design. Lyle's approach emphasized replacing linear systems with cyclical flows, mirroring nature's continuous recycling and cycling of energy and materials. This concept laid the groundwork for regenerative design, focusing on creating systems and environments that are not only sustainable but also contribute positively to the planet's ecosystem. These recent paradigms have advanced from a focus on ultra-efficiency to an effectiveness paradigm, paving the way for the concept of positive buildings (Hafez et al. 2023; Muthumanickam et al. 2023).

The positive buildings are the result of a regenerative framework. This framework shifts the focus from merely minimizing harm towards creating structures that actively heal the environment and enhance occupant well-being. By implementing regenerative principles, buildings can become agents of positive change, fostering a more sustainable and thriving future. These buildings are the result of a multidisciplinary design process that integrates architects' knowledge of construction, material engineering, and energy efficiency(Al-Homoud 2009; Allaire and Willcox 2014; Javanmard and Cascone 2023). The shift towards this new approach is visualized in a transition scenario spanning up to 2085, depicting the evolution from sustainability to regenerative design. Positive buildings go beyond ultra-efficient architectures by not only meeting their energy needs but also producing excess energy, thus aiding in environmental improvement. Key challenges in achieving this include developing integrated, data-driven methodologies for optimal energy performance and surplus generation and creating accurate prediction algorithms for investment and cost analysis. The need for scalable, transferable solutions across multiple buildings is also emphasized. Addressing these challenges can enhance AI-based building energy management systems, with big data, machine learning, and other data-driven approaches playing a crucial role in reducing emissions and energy demands(Ji, Lee, and Yi 2021; Mousavi 2023) (Norouzi et al. 2022). In addition to serving as sources of positive energy generation (PEB), Positive Buildings also function as carbon sequestration agents, thereby contributing significantly to environmental remediation, it means Positive Impact buildings (PIB). This innovative paradigm signifies that such buildings transcend mere carbon neutrality, actively offering additional ecological benefits. to address this goals Renger et al have suggested the Carbon Amortization

Performance (CAP) method has been proposed This approach allows buildings to not only minimize their carbon impact but potentially reverse it, contributing positively to their environments and providing multiple ecosystem services(Churkina et al. 2020; Renger, Birkeland, and Midmore 2015).
To realize the vision of positive buildings that actively benefit the environment, a holistic design strategy is essential. This strategy should engage all sectors of society in a concerted effort to reduce the environmental impact of buildings, with the goal of achieving a carbon-neutral footprint (Kumar and Cao 2021; Lavikka et al. n.d.). The American Institute of Architects (AIA) provides a collection of resources, research, and tools aiming for net-zero emissions in the building sector by 2040, with newest practices and guidance on energy-efficient designs that value sustainable and equitable practices, that is one of appropriate resources related to the holistic design strategy for positive buildings and their impact on achieving a carbon-neutral footprint. An essential component of this strategy is the adoption of a cradle-to-cradle philosophy, ensuring that every phase of a building's life—from inception to deconstruction—is environmentally conscious. Furthermore, buildings should function as repositories for sustainable materials, promoting their reuse and minimizing resource depletion. The integration of green building rating systems, such as LEED or BREEAM, plays a vital role in this context. These systems provide benchmarks for sustainability and encourage the adoption of practices that lead to net-positive outcomes. By embedding these principles and systems at the commencement of the design phase, architects can champion regenerative and innovative practices, ultimately steering the built environment towards greater sustainability(Ascione et al. 2022; Lazar and Chithra n.d.; Mattinzioli et al. 2021).

The transition to positive buildings represents a pivotal shift in architectural design, The upcoming literature review will explore the latest research and technologies employed to achieve this. Positive buildings mark a significant leap from traditional sustainability approaches, ultimately aiming to establish a clear definition through innovative design and methodologies. The review will investigate how these advancements enable buildings to actively contribute to a more sustainable and thriving future.

The promotion of environmentally sustainable buildings plays a pivotal role in the international endeavor to curtail greenhouse gas (GHG) emissions and combat climate change. Against this backdrop, Net Zero Energy Buildings (NZEB) have gained prominence as a principal strategy in numerous countries, aligning with public policies aimed at meeting GHG reduction targets. Research in this domain, exemplified by the study conducted by Felipe Tori and colleagues, delves into the public policies within the residential building sector pertinent to NZEB. The objective of this research is to discern, scrutinize, and juxtapose the mandatory public policies enacted in various countries to foster NZEB. Employing a meticulous literature review with targeted keywords, the study systematically identifies and classifies the public policies from different nations. The outcomes of their analysis suggest that Chile, the focal country of the study, requires the formulation and enforcement of diverse policies to progress toward NZEB. These policies span regulatory, economic, informational, motivational, and advisory realms, underscoring the comprehensive approach necessary for the effective integration of NZEB initiatives within national environmental frameworks.

This insight could be extrapolated to other countries in need of a structured policy framework to support the transition to NZEB(Tori, Bustamante, and Vera 2022).
Achieving a carbon-neutral built environment, specifically within the existing housing stock, presents a critical challenge towards 2050 goals. In his essay, Henk Visscher outlines the innovations required for reaching Nearly Zero Energy Building (NZEB) standards. However, research highlights the inherent difficulty in accurately predicting the long-term impact of laws and regulations on carbon emissions. Previous studies expose the potential limitations of remodelling agreements and calculation methodologies. This suggests that policies and renovation standards may require ongoing adaptation to address external factors such as fluctuating energy prices and the evolving availability of renewable energy resources (Visscher 2019).
To achieve climate change mitigation goals, decarbonizing the building sector is crucial. Yang et al. (2022) developed a spatiotemporal bottom-up dynamic building stock model that integrates material flow analysis, building energy modelling, and life cycle assessment to track material use, energy consumption, and environmental impacts. They applied this model to the residential building stock of Leiden, Netherlands, to evaluate the comparative decarbonization potential of various strategies. The study suggests that the most significant decarbonization is achieved through natural-gas-free heat transition and renewable power supply. Additionally, rooftop photovoltaic installations, greener lifestyles, and wood construction show moderate decarbonization potential, while the impact of demolition waste recycling is less pronounced(Yang et al. 2022b). The modeling approach is shown in Fig (2.4).

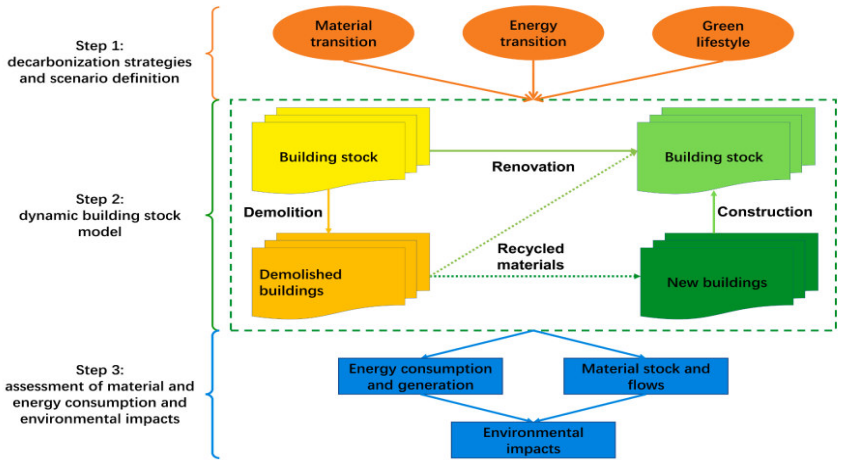


Figure 2-11: The model overview (Reference: (Yang et al. 2022b))

To address the significant role buildings, play in energy consumption and CO_2 emissions, research is increasingly focused on achieving Positive Energy Buildings (PEBs) that generate surplus renewable energy. Rehman et al. (2022) investigated the feasibility of attaining PEB performance in a cold Nordic climate. Their study employed TRNSYS simulation software to model a renewable energy system for a real apartment complex in Finland. This model evaluated the performance of various technologies (photovoltaic-thermal systems, heat pumps, wind turbines, etc.) integrated with the building to meet heating, cooling, and plug load demands, while achieving net positive energy production. A unique aspect of the research is its exploration of PEB performance with extended boundaries, encompassing not just the physical building but also a virtual boundary for exported energy (Rehman, Hasan, and Reda 2022a). Figure 2.5 illustrates this concept of positive energy with extended boundaries.

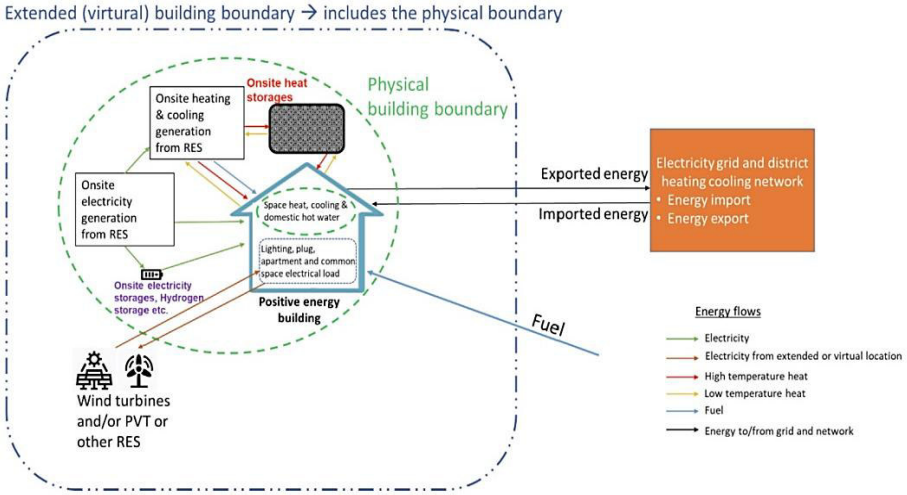


Figure 2-14: The positive energy building concept with the extended boundary that included the physical and extended (virtual) building boundary, (Reference:(Rehman et al. 2022a))

despite of importance of Net Zero Carbon Buildings (NZCBs) as a strategy to reduce carbon emissions, achieving NZCB throughout a building's life cycle presents a challenge, particularly in hot arid environments. To address this gap, El Din Ahmed and Reda (2022) propose a methodology for delivering NZCBs in such climates. Their research focuses on the western desert region of Egypt, a representative hot arid climate in Africa. The study employed DesignBuilder software to perform annual simulations on three models for a single-story dwelling unit (110 m2). Additionally, One-Click LCA software was used to assess the life cycle of carbon emissions over 50 years. The research investigated the combined impact of passive strategies (substitution of traditional building materials) and active techniques (solar panel application). The simulation results demonstrated that by integrating both passive and active strategies, carbon emissions could be reduced by approximately 85%, with energy consumption decreasing by nearly 101%. These findings highlight the crucial role of early implementation and integration of both passive and active technologies for achieving NZCB goals in hot arid climates (Fouly and Abdin 2022a).

Net Zero Energy Buildings (NZEBs) combine passive design and renewable energy to achieve high performance. Benzaama et al. (2021) investigated the potential for a multi-integrated renewable energy system to support NZEB performance in the Mediterranean climate. Their study focused on three specific systems: an earth-air heat exchanger (EAHE), an underground tank (UNT), and a solar thermal collector. Using climate data from Oran, Algeria, the research demonstrated that the combined system outperformed the EAHE and UNT systems operating independently. The integrated system satisfied 131% of the energy needs, compared to 49.3% and 41.7% for the individual systems. Additionally, the combined approach offered significant cost savings (37.9 euros) and carbon emission reductions (21.1 tons) during the heating season (Benzaama et al. 2021).

Achieving deep decarbonization targets within the building sector requires a holistic approach addressing both embodied and operational greenhouse gas (GHG) emissions throughout the building life cycle. Vahidi et al. (2021) investigated regional variations in GHG mitigation strategies within the U.S. building sector. Their research highlights that GHG reduction potential is influenced by both geographic location and building type. This underscores the need for context-specific prioritization of mitigation

strategies. While operational emissions will remain a major contributor, the study suggests the necessity for a dual focus on both embodied and operational sources to meet decarbonization targets (Vahidi et al. 2021).

To achieve comprehensive urban sustainability, the retrofitting of older buildings should be prioritized alongside the design of new structures that adhere to Nearly Zero Energy Building (NZEB) principles. Research by Monzon-Chavarrías et al. specifically examines the application of NZEB standards to the renovation of multi-family residential buildings constructed between 1961 and 1980 in Portugal and Spain. This study offers a focused analysis, examining how improvements to building envelopes and active systems can lead to compliance with NZEB requirements. Results indicate that applying NZEB standards during the renovation of these buildings can drastically reduce CO_2 emissions. However, the study suggests potential refinements to NZEB regulations, specifically regarding major renovation criteria in Portugal and the integration of renewable energy sources in Spain (Monzón-Chavarrías et al. 2021).

European Union programs, notably Horizon 2020, actively promote the evolution of Nearly Zero Energy Buildings (NZEB) towards the Positive Energy Building (PEB) model. Magrini et al. provide a critical analysis of key European Union initiatives driving the development of PEB design. Their study explores the integration of innovative technologies and materials (such as PCM, VIP, smart glass, and photovoltaic systems) within the NZEB framework. The review examines the evolution of these design models, highlighting recent elements that support NZEB targets. A case study demonstrates how the integration of building envelope and systems design, combined with renewable energy sources, can achieve near-total energy coverage (Magrini et al. 2020).

Building energy efficiency upgrades are essential for mitigating global warming and aligning with the European strategy for achieving energy and climate goals. D'Agostino and colleagues emphasize the value of Nearly Zero Energy Buildings (NZEBs), defined by their very low energy consumption. This goal is achieved by minimizing energy needs while maintaining comfort and air quality, maximizing the efficiency of building systems, and utilizing renewable energy sources. NZEBs are quantified by their non-renewable primary energy consumption (kWh/m2/year), with calculations guided by national, regional, and European standards (D'Agostino and Mazzarella 2019).

Researchers led by Ruggiero propose an innovative retrofit system for urban buildings, aiming to achieve positive energy performance. This system, designed in collaboration with Arca Puglia Centrale, integrates conventional heating/cooling systems with renewable energy sources like solar panels and vegetation elements. The modular design allows for adaptation to various building shapes, environments, and climates. This method offers a promising approach for transforming existing public housing stock into positive energy buildings, aligning with European energy efficiency directives (Ruggiero, Di Turi, and Mastrorilli 2018)

A study by Kalaycoglu et al. explores a cost-effective strategy for achieving NZEB goals in building districts, particularly in Turkey. While expensive renewable energy systems are often seen as a requirement for NZEBs, this research proposes a staged approach. The study suggests that by initially focusing on building-level energy efficiency measures (e.g., improved insulation) alongside existing on-site renewable energy sources, substantial energy savings can be achieved. Further reductions in energy consumption can then be targeted at the district level through the implementation of shared systems like district heating and cooling. This two-pronged approach offers a potentially more affordable strategy for achieving NZEB compliance, while also

investigating the overall costs associated with NZEB in both buildings and districts (Kalaycıoğlu and Yılmaz 2017).

Many studies have been done to examine various methods of reducing the embodied carbon in buildings. Akbarnezhad, et al Classified five broad categories for these tactics:1-low-carbon materials, 2- material minimization and material reduction strategies, 3- material reuse and recycling strategies, 4- local sourcing and transport minimization, 5- construction optimization strategies (Akbarnezhad and Xiao 2017).

Stated the studies have been done the concept of positive energy buildings (PEBs) is a rapidly evolving field within sustainable building design. A key challenge lies in establishing a universally accepted definition. A 2021 workshop at the Sustainable Places Conference, led by Ala-Juusela et al. (2021), aimed at bridging this gap by analysing existing definitions from ongoing research projects. The workshop identified a crucial distinction between PEBs and zero-energy buildings (ZEBs): PEBs not only achieve energy self-sufficiency but also contribute surplus energy to the surrounding grid (Ala-Juusela, Crosbie, and Hukkalainen 2016).

The workshop discussions on defining positive energy buildings (PEBs) concentrated on three principal areas: firstly, the delineation of physical boundaries and the selection of energy types for the energy balance calculation, emphasizing the comprehensive accounting of a building's energy consumption. Secondly, attention was given to the interaction between PEBs and the energy grid, with a particular focus on the contrast between the flexibility of "active buildings" that interact dynamically with the grid and "passive buildings," which depend solely on grid energy, highlighting the necessity of optimizing on-site renewable energy production and consumption. Lastly, the discourse extended to social factors, examining how occupants interact with the building and its indoor environment, underscoring the challenge of harmonizing human-centric design and user-friendly systems with intricate control strategies to minimize energy use, thus reflecting a holistic approach to the conceptualization of PEBs. In the discourse on Positive Buildings (PB), it is imperative to consider two fundamental aspects: Positive Energy (PEB) and Positive Impact (PIB). A building qualifies as a PEB when, owing to its exceptional energy efficiency, its total annual primary energy consumption is less than or equal to the energy supplied to it from renewable sources. The evaluation of net-positive buildings diverges from net-zero buildings in that the former's objectives extend beyond mere energy conservation. Net-positive buildings aspire to confer added value to users and occupants, potentially manifesting as enhanced productivity, improved well-being, and energy savings that transcend the building's immediate confines. Cole et al. (2015) assert that the focus should not solely be on generating surplus energy for export over what is imported to the buildings or the grid. Instead, a systemic approach should be adopted to optimize energy performance (Cole 2015). While net-positive energy buildings share many principles and technologies with net-zero buildings, they introduce novel paradigms such as networking or district-level energy considerations and the utilization of alternative energy resources aside from renewables. Furthermore, a positive building encompasses more than achieving zero carbon emissions; it actively contributes to environmental quality by mitigating pollution and absorbing environmental contaminants, thus exerting a positive impact on the surrounding ecosystem.

Summary:

The escalating climate crisis, coupled with the built environment's significant environmental impact, demands a fundamental shift in architectural paradigms. According to the results of contemporary research, positive buildings represent an advancement beyond the paradigm of zero-energy and zero-impact construction. These edifices not only generate sufficient energy to meet their own consumption requirements but also have the capacity to contribute surplus energy to the neighbouring grid infrastructure (Fig 2.6).

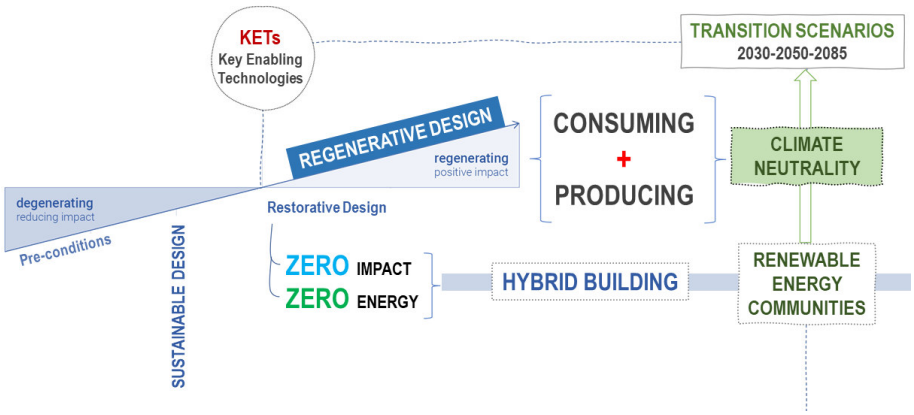


Figure 2-17 : Transition scenarios 2030,2050,2085

Moreover, it has been observed that the levels of embodied carbon and operational carbon emissions in positive buildings are not merely neutralized but are surpassed, thereby contributing to a net-negative carbon footprint. Additionally, the environmental pollution associated with these buildings is significantly reduced, underscoring the importance of adopting and promoting positive building practices in the broader context of sustainable urban development (Figure 2.7).

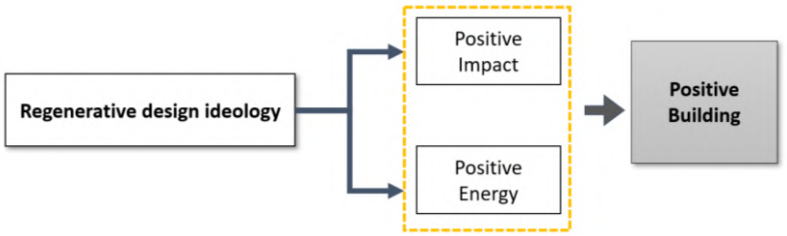


Figure 2-20: Positive building approach (Reference: Author)

The literature on positive buildings reveals that researchers have employed various strategies to design environmentally sustainable structures, categorizing their approaches broadly into two types: active systems and passive design and construction systems. Active systems primarily involve the deployment of innovative technologies and the utilization of renewable energy sources, such as solar, wind, and wave energy. These systems are pivotal in achieving low-carbon energy solutions by harnessing natural processes. Conversely, passive design and construction systems emphasize the use of recycled and upcycled materials, alongside exploiting climatic potentials to optimize building design. This includes strategies like daylighting, natural ventilation, rainwater harvesting, vertical transportation, shading, and green roofing. These methods also advocate for the creation of forms appropriate to local climatic

conditions, the selection of locally available and durable materials, and overall climate-responsive design.

Integrating these systems through a cohesive design management approach is essential for realizing the objectives of positive construction, which aims to create buildings that have a net positive impact on the environment. In general, most researches further delves into nature-centric solutions categorized into nature-based, nature-derived, and nature-inspired approaches. Nature-derived solutions leverage elemental forces such as wind, wave, and solar power, translating these into sustainable energy outputs. Nature-inspired solutions, including biomimicry, draw on biological processes to inform the design and production of materials, structures, and systems. Meanwhile, nature-based solutions exploit ecosystem services to provide natural benefits to both society and the environment.

This synthesis of varied approaches underscores the multidisciplinary nature of positive building design and sets the stage for a detailed exploration of these solutions in subsequent chapters, highlighting the innovative integration of natural elements into sustainable architectural practices.

Positive buildings offer a compelling vision for the future, where buildings transcend mere sustainability to actively contribute to ecological restoration and regeneration. While the full potential of positive buildings remains to be realized, this review has illuminated a clear path forward. As depicted in Diagram 2, achieving positive buildings necessitates a comprehensive and integrated design framework.

This framework demands collaborative efforts from various societal sectors to mitigate the environmental impact of construction and propel us toward a zero-carbon future. Underpinned by a cradle-to-cradle approach, this framework requires a thorough consideration of a building's entire lifecycle. Buildings should function as repositories for sustainable materials, emphasizing reuse and minimizing resource depletion. By synthesizing diverse approaches from experts in the field, this framework offers an exhaustive strategy for the conception of positive buildings. It encapsulates the best practices and innovative approaches identified to date, highlighting the vital role of regenerative design principles in the early stages of the architectural process. This methodology fosters innovation and deeply ingrains sustainability in the built environment. However, it is important to acknowledge that this framework, while robust, is not static. It remains amenable to progression and refinement in response to novel breakthroughs and scholarly contributions within this rapidly evolving domain. The field of positive building design is dynamic, and continuous advancements in science and technology will undoubtedly offer new insights and methods. Therefore, the framework we have established should be viewed as a living document, receptive to future developments and innovations that can further refine and improve the design and functionality of positive buildings. This adaptability ensures that the framework remains at the forefront of architectural practice, contributing to the ongoing effort to achieve ecological balance and sustainability in our built environments. The realization of positive buildings requires continuous innovation and collaboration across disciplines. Emerging technologies, such as AI-driven energy management systems and advanced data-driven methodologies, will play a crucial role in optimizing energy performance and environmental impact assessment. Diagram 2.1 shows a summary of the Positive Design Process that the researcher followed through this research.

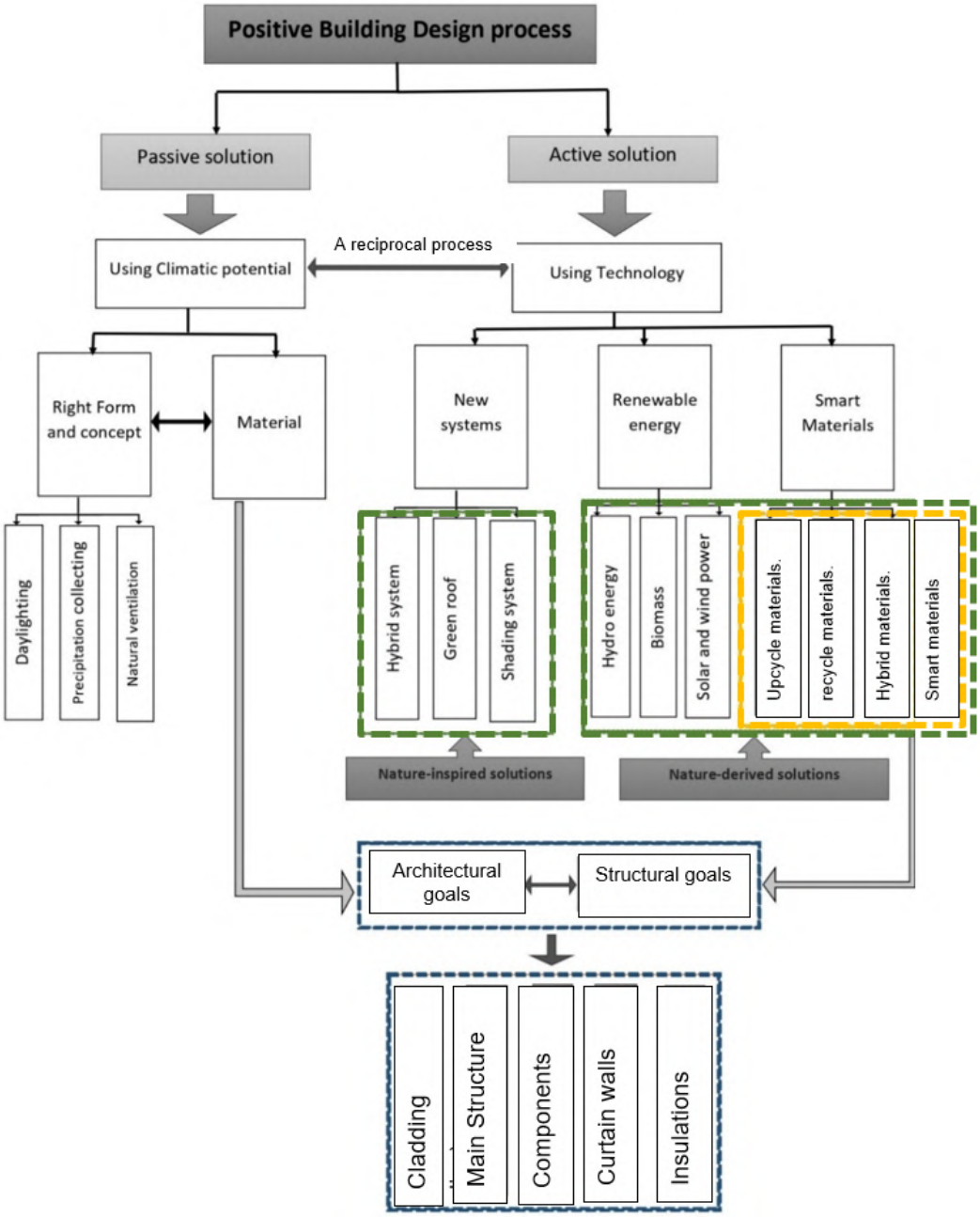


Diagram 2-2: Positive design Process (Reference: Author, ABITAlab), Appendix C, Page 392

2.6 Use of Materials in Sustainable Architecture

In various paradigms, materials constitute a critical component in architectural and structural design, particularly within the context of sustainability. These materials exert environmental impacts throughout their lifecycle, which encompasses stages such as raw material acquisition, manufacture, production, use, reuse, maintenance, and ultimately, waste management. The construction industry significantly impacts waste generation, with recent figures indicating 536 million tons of construction waste and an additional 33 million tons from new constructions. This starkly contrasts with the 268

million tons of municipal solid waste, underscoring the substantial contribution of the building sector to landfill mass. Moreover, construction activities are major contributors to global energy consumption and emissions, highlighting the pressing need for sustainable material management and design practices in the construction industry (Figure 2.8).

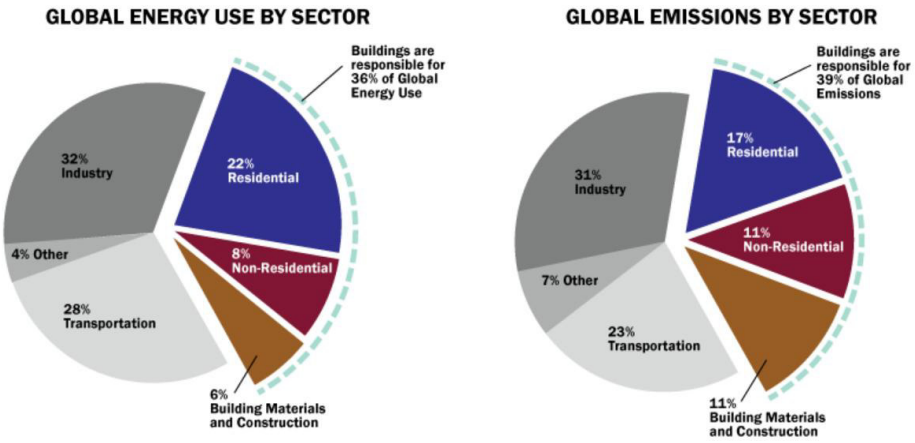


Figure 2-23: Data from 2019 status Report for Building and construction (*https://www.archtoolbox.com/*),

Materials hold the key to transforming architecture from a merely sustainable practice to a truly regenerative one (Figure 2-9). Within the regenerative design paradigm, the choice of materials transcends mere functionality. They become active agents in environmental restoration and social well-being. As Attia (2017) emphasizes, a robust architectural framework is essential to guide designers in selecting materials based on three core principles: safety, reusability, and their ability to support renewable energy systems. This framework ensures that material choices align with the broader goals of regenerative design, fostering a positive impact on the environment and society (Attiya 2018).

The centrality of materials in architectural paradigms, particularly regenerative design, is underscored by their significant environmental footprint at every stage of their lifecycle. This lifecycle spans from raw material acquisition through to end-of-life stages, including manufacturing, usage, and waste management (Estokova and Samesova 2021; Javanmard 2022; Javanmard and Nava 2022a). The pivotal role of materials arises from their potential to substantially impact the environment, as evidenced by the construction industry's substantial contribution to global waste and emissions (Cuerda and Rivela 2013). Data from the 2019 status report for building and construction reveal the sector's significant energy use and emissions, while the US EPA's 2017 fact sheet highlights the 569 million tons of construction and demolition waste generated in the United States, underscoring the urgency of responsible material management (US EPA, 2017). In the past, material selection in architectural design was often an afterthought, with the primary focus on aesthetics and spatial functionality. However, with the advent of environmental consciousness and the emergence of sustainability as a key goal in design, the choice of materials has gained prominence. Materials are now recognized for their ability to reduce the environmental pollution associated with building operations, aligning with the principles of various architectural paradigms, especially the emergent regenerative design (Dixit and Stefańska 2022).

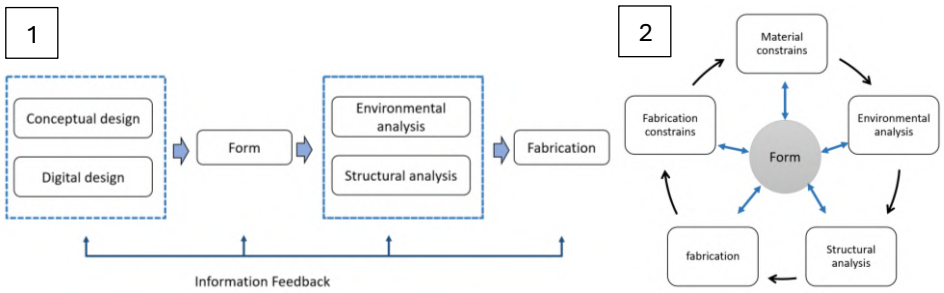


Figure 2-26: 1)current designing process, 2) material-based design process, (reference: Dixit And Stefanska,2022)

The regenerative design paradigm goes beyond mere efficiency; it requires a comprehensive evaluation of a material's lifecycle, from extraction to potential reuse or recycling, reflecting a cradle-to-cradle mentality. This approach emphasizes the necessity of selecting materials not just for their structural and functional properties, but also for their environmental credentials (Abdullah and Al-Alwan 2019) Regenerative design posits that buildings should act as material banks, with a slower consumption rate that matches the planet's capacity for regeneration. By utilizing C2C-certified materials or those with similar eco-friendly credentials, architects can ensure their projects contribute less waste and fit within the cycles beneficial to the biosphere or Technosphere. The importance of materials in architectural design, particularly within regenerative paradigms, can also be anchored in emerging research that advocates for the use of bio-based materials and the integration of innovative technologies for material processing. These advances can lead to not only environmentally sustainable outcomes but also economic and social benefits, aligning with the broader Sustainable Development Goals as set by the United Nations (UN, 2015). The strategic selection and management of materials are fundamental to advancing sustainable architectural practices and achieving the goals of regenerative design. This consideration is integral to creating buildings that harmonize with the environment, conserve resources, and support the well-being of society.

The positive building approach and the Cradle-to-Cradle (C2C) concept envision buildings as resource repositories rather than sources of waste. This shift involves transforming linear product lifecycles into a regenerative "take, make, renew" model (Muhammad and Al-Masry 2019). Within this framework, designing buildings as material banks aligns with three key C2C principles: eliminating the concept of waste through continuous reuse, prioritizing renewable energy sources, and rethinking end-of-life for materials and components to enable disassembly and repurposing. By embracing these principles, the positive building paradigm promotes a circular materials economy that aligns with the Earth's regenerative capacity (Figure 2.10).

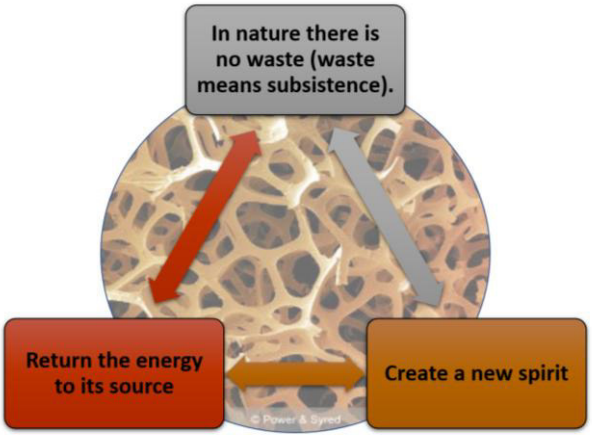


Figure 2-29: 3Vital principles for life cycle materials in C2C concept, (Reference: (Muhammad and Al-Masry 2019)

Figure 2-11 highlights the vast potential of materials within the built environment to be recovered and reintegrated into consumption cycles. By prioritizing reuse, upcycling, and design for disassembly, the embodied value of building materials can be continuously harnessed. This approach supports the shift towards a circular materials economy, minimizing the need for virgin resource extraction and furthering the sustainability goals of the built environment. To fully realize this potential, a critical next step involves developing innovative strategies and frameworks to optimize the recovery and reintegration of materials within the construction industry.

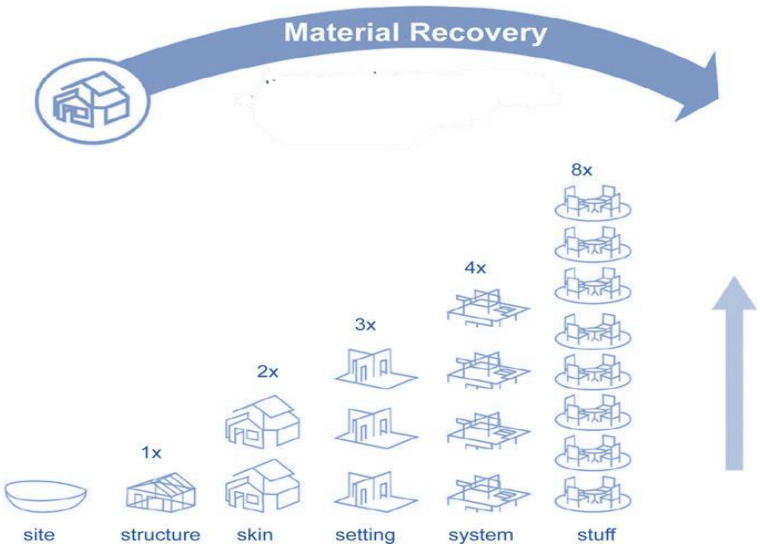


Figure 2-32:Number of time material and systems cycle through a building in a single lifetime, Steward brand— how buildings learn (1994)

Contemporary architectural discourse involves diverse perspectives on material selection for both structural and aesthetic purposes. Some prioritize innovative "smart" materials for aligning with sustainability goals, while others advocate for reused or recycled materials to minimize embodied carbon. Another approach emphasizes locally sourced materials, leveraging their intrinsic suitability to regional climatic conditions.

Determining a universally superior material strategy is challenging due to project-specific constraints. What is clear is that to choose the right material to address environmentally friendly buildings Rigorous assessment of materials throughout the

building's life cycle is crucial. This analysis should evaluate environmental impacts, the use of renewable energy in production, and the potential for the safe return of materials into industrial or natural systems at the end of their life.
Environmental degradation and rising greenhouse gas emissions propel communities towards the urgent need for positive buildings. Ambitious sustainability targets, particularly within Europe, require a strong focus on the role of construction materials. Researchers engaged in sustainable development recognize the value of materials as a passive solution for improving building quality.
Crucial considerations for environmentally conscious buildings include informed material selection, recycling practices, and end-of-life disposal strategies. From structural elements to finishes, materials must prioritize energy efficiency while minimizing their environmental footprint. Recycled and upcycled materials, coupled with enhanced building envelope performance, offer promising solutions for an increasingly eco-friendly architecture.

The following sections will delve into specific research contributions within this field:
The selection of building materials is intrinsically linked to a building's climatic design. In contemporary architecture and construction, a growing focus lies on utilizing local materials, not only for aesthetic reasons but also for their ability to respond effectively to the local climate. To become an effective builder with local materials, designers must understand and apply the principles of local design, ensuring new buildings are well-adapted to their environment (Javanmard and Nava 2022b).
Conducting comprehensive research on alternative materials is crucial for the development of environmentally friendly buildings, with a focus on their physical, chemical, and engineering attributes. Nitu et al. (2023) underscores the significance of these materials in diminishing environmental impacts and fostering sustainable habitats that are beneficial for occupants and the surrounding environment. Their analysis includes a comparison between alternative and traditional materials, highlighting critical factors. These alternative materials, which range from locally sourced and recycled or salvaged substances to repurposed construction waste, present numerous advantages. They contribute to lower pollution levels, economic viability, decreased environmental footprint, enhanced thermal performance, reliance on renewable sources, effective use of industrial by-products, reduced emissions, and overall financial practicality (Nitu et al. 2023).
Recycling waste into valuable new products is fundamental to achieving the environmental and economic goals of sustainable development and a circular economy. Geopolymers, a class of materials known for their eco-friendly properties, excellent mechanical performance, and ability to utilize various waste streams as precursors, have gained significant interest. While research on geopolymers is extensive, geopolymer concrete (GeoC) remains an under-explored area with substantial potential. Studies by Nabila Shehata et al. demonstrate the promise of GeoC as a green construction material. Their research, which adheres to the Preferred Reporting Items for Systematic Reviews (PRISMA) guidelines, highlights the ability to develop GeoC matrices from diverse industrial, municipal, and agricultural waste sources. This utilization of waste materials not only reduces manufacturing costs but also contributes to the creation of a closed-loop, environmentally friendly construction sector (Shehata et al. 2022).
The potential of geopolymer concrete as a sustainable material has been demonstrated in Figure 2.12.

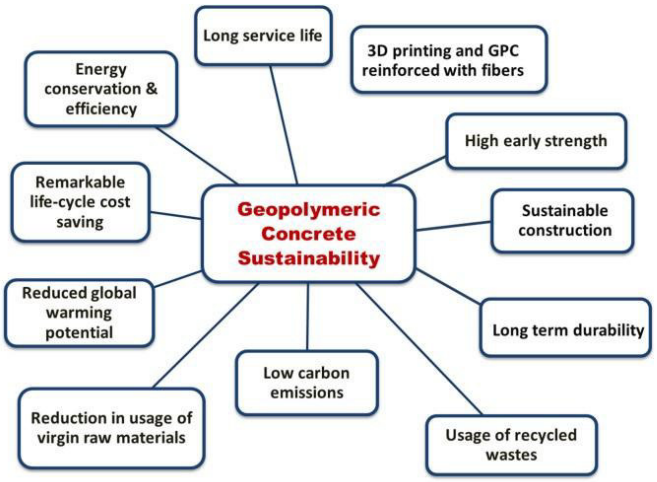


Figure 2-35: Benefits of Geoc in Construction which are also considered the reason for their sustainability (Reference: Shehata et al. 2022)

The reuse of solid waste in building materials offers a promising pathway towards achieving zero-carbon emissions goals in the construction industry. Fodzi et al. (2020) conducted a comprehensive review examining various methods for recycling and reusing solid waste in building materials. Their research suggests that incorporating solid waste into materials like concrete and bricks can result in lighter-weight products with improved water absorption, compressive strength, plasticity, and energy efficiency. These findings highlight the potential for transforming waste materials into valuable construction resources, reducing emissions, and promoting a more sustainable built environment (Muhammad Haikal Mohd Fodzi 2020.d.).

Incorporating waste materials into sustainable external façade panels, designed for recyclability at the end of their life cycle, offers a powerful way to reduce a building's environmental footprint and conserve natural resources within a circular economy model. Growing concerns about climate change and global resource management have propelled a search for innovative design approaches that foster a more balanced relationship between the built and natural environments. Inspired by principles of resource circularity found in nature, the circular economy presents a compelling alternative to traditional linear economic models. Research like that conducted by Sarah Parece et al. explores the potential of transforming local urban and industrial waste streams into sustainable construction materials. Their study, based on Ashby's methodology and utilizing multi-criteria decision aid (M-MACBETH), evaluates a wide range of upcycled and recycled materials, such as plastics, wood, paper, metals, and agricultural waste, for potential use in partition walls. This research highlights the promise of innovative material solutions within a circular framework for a more sustainable built environment (Fouly and Abdin 2022b).

Utilizing waste materials to fabricate sustainable external façade panels, which are recyclable at the end of their lifecycle, can significantly mitigate the environmental footprint of buildings. Bagari et al. investigated the use of recycled construction and demolition waste (CDW) for producing ventilated prefabricated wall panels in their study. Their findings indicate that the developed panels are not only robust and moisture-resistant but also capable of enduring high temperatures. This innovation in using recycled CDW for façade panels exemplifies a sustainable approach in building design, contributing to the reduction of waste and promoting environmental sustainability in the construction sector (Bagarić, Pečur, and Milovanović 2021).

Climate and environmental conditions have a special and inevitable physical and psychological effect on humans that should be considered in the design of buildings depending on the heating or cooling situation.The building's outer skin is the interface between the interior and exterior. The complex design of the skin can bring the issue of energy consumption optimization closer to the ambitious goals of energy saving through environmental considerations (Zemella and Faraguna 2014) An important function of the outer skin of the building (decking of space frames) is to control environmental and physical factors such as light, heat, sound, etc. to achieve comfort conditions with minimal energy consumption (Oral, Yener, and Bayazit 2004a). Various simulation programs have been developed for this purpose that can lead the design solutions to the optimization of the building by simulating the building and measuring the exact energy consumption. Z.Javanmard And C.Nava ,2022 investigated the effects of aluminium ang glass on two different forms of spatial structures considering a special climate (hot and dry). To research the environmental impact on choosing the construction method and to select a more appropriate climatic material, all models were built and analysed with Design-Builder, the result shows that the best form and material for hot and dry climates is the dome with aluminum with several openings, that it is better were considered to use for special times and date during the year (Javanmard and Nava 2022c).

Building facades serve as the building's "skin," providing a critical barrier against external elements while offering a glimpse into the interior. Beyond aesthetics, facades must meet various performance requirements, including strength, flexibility, insulation, and durability. Fiber-cement panels, particularly those reinforced with sustainable materials like vegetable or textile waste, have emerged as a promising solution for architects seeking to balance performance with environmental responsibility. Research Sara Parece et al.2022 explores a novel methodology for objectively assessing the sustainability of facade cladding panels. Their model, focusing on fiber/textile-reinforced cement sheets, highlights the importance of considering material selection throughout the design process to achieve a balance between performance and environmental impact (Parece et al. 2022).

Reducing energy consumption during the operational phase is a critical consideration in material selection, particularly against the backdrop of increasing urbanization and demand for energy efficiency. Building insulation materials, such as expandable polystyrene (EPS) foam, have become vital due to their lightweight, effective thermal insulation, and overall performance. However, the inherent flammability of EPS raises substantial safety concerns. While traditional flame-retardant coatings offer some protection, they often contain hazardous chemicals, including formaldehyde. Addressing this issue, Wei Zhao and colleagues have innovated a new, formaldehyde-free, phosphorus-containing polydioxanone coating that acts as both an adhesive and flame retardant for EPS foams. This development represents a significant step forward in improving the safety and environmental profile of EPS insulation materials, paving the way for safer and more sustainable construction methodologies (Zhao et al. 2022).

The external materials used for building claddings, being the critical interface between the interior and exterior spaces, play a pivotal role in energy consumption optimization and carbon emissions reduction. This aspect is of paramount importance across various architectural paradigms such as sustainable design, green design, ecological architecture, and climatic design. In the realm of optimizing design for energy efficiency, smart glazing emerges as a significant element, particularly for office spaces. A systematic study conducted by Moncef Krarti on the ideal optical

characteristics of smart glazing aimed to reduce energy consumption in perimeter office areas. The findings underscore that smart glazing, integrated with daylighting controls, can significantly enhance energy efficiency in office buildings, especially in cold climates with large window areas. This analysis facilitates the determination of optimal optical properties for smart glazing, considering various factors, including climate, window size, and orientation, thus contributing to the advancement of energy-efficient architectural designs (Krarti 2022).

In efforts to enhance the exterior facade of buildings, Cindy P.K. Yeung and colleagues have made significant strides through their research on thermochromic coatings for glass. Their study, which focused on the phase separation of VO_2 and SiO_2 on SiO_2-coated float glass, resulted in a robust thermochromic coating with exceptional optical properties. This innovative coating demonstrated a substantial positive impact on energy savings for both heating and cooling in buildings situated in moderate climates. Utilizing building energy simulations, the effectiveness of this coating was quantified, revealing potential energy savings of up to 24% for a typical house in the Netherlands. This research underscores the potential of advanced coating technologies in reducing energy consumption and enhancing the overall energy efficiency of buildings (Yeung et al. 2021).

Glass coverings play a crucial role in safeguarding solar cells from the detrimental effects of irradiation and corrosion, particularly in outdoor photovoltaic (PV) equipment applications. However, the performance of these glass coverings can be significantly compromised under harsh weather conditions like dust accumulation, wind erosion, and precipitation, leading to reduced optical transmittance and consequent energy production losses. In response to this challenge, Chaoyou Tao and Lin Zhang conducted a study to address these issues. They developed a methodology for creating multifunctional closed-surface SiO_2-TiO_2 antireflective thin films. This innovation entails a glass layer characterized by high moisture resistance at elevated temperatures and effective performance, attributed to its closed-surface structure, offering a promising solution to enhance the durability and efficiency of solar panels in extreme weather conditions (Tao and Zhang 2020).

Existing buildings are a significant source of environmental pollution; thus, their rehabilitation, retrofit, and refurbishment present substantial opportunities to reduce energy waste and combat global warming. Demolishing these structures can generate considerable waste. However, enhancing their thermal characteristics through material improvements can significantly reduce energy consumption. Implementing multi-layer interior insulation is an economical method to convert existing houses into nearly zero-energy buildings (NZEB). The market offers a diverse array of building envelope products, each with its environmental footprint.

In their research, Amani and Kiyaee introduced a methodology for devising a two-criteria framework to evaluate thermal insulation materials for building envelopes, aimed at optimizing energy efficiency while minimizing environmental impact. This approach led to the identification of eight Pareto-optimal solutions that substantially lower energy consumption in a typical multi-story apartment building, achieving over a 70% reduction in energy usage and presenting a global warming potential range of 192-1500 kg CO_2 equivalent. This study underscores the potential of targeted insulation enhancements in significantly improving the energy efficiency and environmental performance of existing buildings (Amani and Kiaee 2020b).

Smart glazing can lead to energy savings ranging from 1.2% to 13.3% over static glazing, with the actual savings dependent on daylighting configurations and climatic conditions. Achieving the maximum energy efficiency gains from smart glazing in office buildings requires optimizing a specific set of optical properties for both its clear and tinted states. B.Geetha Priyadarshini and colleagues explored this topic, conducting a systematic study to determine the ideal optical characteristics of smart glass that would minimize energy consumption in perimeter office spaces. Their research aimed to identify the optimal configurations that would enhance the energy-saving potential of smart glazing, thereby contributing to more efficient and sustainable building designs (Geetha Priyadarshini and Sharma 2016).

Beyond the impact of materials on energy consumption, the durability of these materials emerges as a crucial aspect that must be considered in selecting materials for building construction. In façade design, the choice of constructive solutions is pivotal, and materials should be resilient against anticipated degradation agents and mechanisms. Despite the significance of this decision, it often relies on intuitive criteria. Cláudia Ferreira and colleagues have addressed this gap by examining the long-term behavior, maintenance requirements, and costs of various cladding systems through a multi-criteria analysis methodology. Their evaluation encompassed investigating the performance of six common façade cladding materials (ceramic tiles, natural stone, rendered finishes, painted surfaces, ETICS systems, and architectural concrete) under real-world conditions in Portugal. By analyzing how these materials degrade over time, the study establishes a data-driven framework to guide façade cladding selection. Their findings indicate that the "optimal" cladding choice depends on various factors, including project priorities and building owner preferences. This framework empowers decision-makers to choose more suitable and cost-effective materials while optimizing maintenance strategies. The study highlights that prioritizing maintenance plans can have a smaller impact (around 1%) on cladding selection compared to construction solutions (at least 17% impact), which are more significantly influenced by initial cost considerations and the absence of preventative maintenance practices (Ferreira et al. 2021).

Summary:

In the conclusion of the literature review section on materials for positive building, it is imperative to underscore that material conservation in green building construction is not merely a preference but a necessity for developing sustainable structures. The selection of structural materials during the building design process must prioritize ecological compatibility to enhance the sustainability of construction practices. Environmentally benign materials in green design are characterized by their superior thermal performance, energy, and water efficiency, effective resource management, and their contribution to reducing overall construction costs.

Furthermore, the selection process for materials in positive building construction must incorporate the consideration of embodied carbon, highlighting that material selection criteria extend beyond immediate environmental benefits. This necessitates a comprehensive evaluation of the long-term environmental impacts associated with materials, underscoring the importance of a holistic view in material selection. Therefore, to align with the principles of positive building practices, the adoption of materials that are eco-friendly, durable, resource-efficient, and non-toxic is essential. For the realization of truly sustainable habitats, attention must be focused on materials

that are ecological, recycled, upcycled, and economically viable. Such materials are pivotal in fostering construction practices that are environmentally responsible. The literature identifies several key attributes of green building materials, which include:

- Recycled Products
- Materials Manufactured through Environmentally Friendly Processes
- Natural or Renewable Materials
- Refurbished or Salvaged Items
- Reusable and Recyclable Products
- Durable Materials
- Incorporation of Water and Energy-Saving Technologies
- Non-toxic Materials

In the context of contemporary architectural technology, there is a significant discourse surrounding hybrid materials, which are posited as advantageous for positive building infrastructures. These hybrids or 'smart materials' are defined by their capacity to undergo reversible changes in properties when subjected to external stimuli such as light, temperature, electrical charge, or other physical or chemical influences. NASA's definition of "smart materials" as those capable of "remembering configurations and adjusting to specific stimuli" underscores the advanced functionality of these materials. This has led to a focused interest in highly integrated, multifunctional façade systems (hybrid cladding) that utilize sustainable materials, blurring the lines between physical and spatial boundaries.

2.7 The Rold of Geometry In Architecture

The role of geometry in architecture spans across historical, modern, and contemporary paradigms, serving as a fundamental element in shaping sustainable design solutions. Traditional architectural styles, such as vernacular and classical architecture, integrate geometric principles with local climate conditions, available materials, and cultural norms. As architectural practices evolve, modern and contemporary designs prioritize environmental sustainability and adaptability, leading to the emergence of sustainable architectural paradigms like Sustainable and Bioclimatic Architecture, Green Architecture, and Carbon-Neutral Architecture. These paradigms leverage geometry to optimize natural resources, minimize environmental impact, and enhance building performance. Additionally, advancements in Parametric and Computational Architecture enable complex, fluid designs that respond to environmental and material efficiency factors. Digital Architecture further extends these principles, leveraging digital technologies for design, visualization, and optimization of building performance. The following literature review explores the historical evolution of geometry in architecture and how architects have applied geometric principles to address sustainable building challenges.

(Besir & Cuce, 2018).In the realm of architecture, the application of geometry has been both a functional and aesthetic cornerstone across various historical styles (Leopold and Cornelie 2006). In traditional or vernacular architecture, geometry often emerges from the use of local materials and construction methods, exemplified by the circular shapes of indigenous yurts in Central Asia and the rectangular forms of classic European

timber framing (Gonsalves,2020)(Pardo 2023; Samalavičius and Traškinaitė 2021). These geometric forms are not merely aesthetic; they are deeply rooted in responding to local climate conditions, available materials, and cultural norms (Henna, Saifudeen, and Mani 2021). Transitioning to classical architecture, such as the Greek and Roman styles, geometry becomes even more pronounced. The emphasis on symmetry, proportion, and the use of basic geometric shapes like circles, squares, and triangles is central (Duvernoy 2018). These geometrical principles are vital not only for achieving aesthetic harmony and balance but also for ensuring structural integrity and efficient material utilization. In Gothic architecture, geometry evolved further to include pointed arches, ribbed vaults, and flying buttresses. These elements are not just stylistic choices, but also serve critical functional purposes (Romano and Ochsendorf 2010). They enable the construction of higher ceilings and larger windows, enhancing the infusion of light and creating an impression of height and lightness. In Gothic structures, geometry thus plays a dual role, both supporting larger, more ambitious architectural forms and contributing to the unique aesthetic character of the style(John H. Harvey 2011). Throughout these architectural periods, geometry stands as a testament to the fusion of form, function, and artistic expression, showcasing the adaptability of architectural practices to various cultural, environmental, and material contexts (Maira Vidal 2017). In the evolution of architectural styles, modern and contemporary practices represent a significant shift from their historical predecessors, embracing simplicity, functionality, and a deepened focus on environmental considerations (Dapogny et al. 2017). Modernism marked a departure from ornate styles, favoring clean lines and geometric simplicity. In the early 21st century, the rapid pace of urbanization, which has disturbed ecological equilibriums, has brought into focus the significance of building envelope technologies in the realm of sustainable building practices and the shaping of urban spaces(Besir & Cuce, 2018). Within the evolving architectural paradigm, the conceptualization and architectural design of roofing structures has been subject to an ongoing process of evolution, marked by a series of challenges and a plethora of innovative developments. This trend reflects the dynamic nature of architectural practices and their adaptive responses to emerging needs and technological advancements. In fact, traditional wisdom has influenced modern sustainable design practices, where geometry continues to play a crucial role in enhancing building performance and reducing environmental impact.

To address environmental concerns, architectural paradigms have progressively shifted towards sustainable, green, eco-architecture, and regenerative design (Villacis-Ormaza 2024). This transition underscores an escalating emphasis on environmental sustainability within the field of architecture. In these paradigms, geometry plays a pivotal role, serving as a fundamental element in shaping sustainable design solutions (Brown and Mueller 2016). In the realm of sustainable architectural paradigms, the role of geometry has been increasingly recognized as pivotal in addressing environmental challenges. This shift is a continuum from historical practices to modern innovations (Kistelegdi et al. 2022)(Thi and Le 2020). With the advent of Sustainable and Bioclimatic Architecture, a response to growing environmental concerns, the geometric design of buildings has been meticulously considered to optimize natural resources such as sunlight and airflow. This involves strategic building orientation and window placement to harness solar energy and enhance natural cooling (Du 2019). Further exemplifying this trend is Green Architecture, where geometric designs are specifically tailored to minimize environmental impact, focusing on energy efficiency and positive ecological contributions (Attya, Habib, and Al-Obaybi 2015). This approach integrates renewable

energy systems and sustainable materials, aiming to reduce buildings' carbon footprints (Tkachenko and Mileikovskyi 2019). The concept of Carbon-Neutral Architecture takes these principles a step further by aiming for a net-zero carbon footprint (Liang et al. 2023). Geometry plays a crucial role in these designs, optimizing the use of renewable energy sources and minimizing energy consumption (Boyer et al. 2010) (Vassigh and Spiegelhalter 2014)(Ciacci 2020). Regenerative Architecture represents the cutting edge of this evolution, transcending sustainability (Attia 2016). Here, buildings are designed not just to minimize harm but to actively improve their environment. Geometry in this paradigm is employed to create spaces that contribute positively to ecosystems and communities (Attiya 2018). Additionally, the emergence of Parametric and Computational Architecture has introduced advanced software-enabled complex, fluid designs adaptable to various environmental and material efficiency factors (Natanian, Aleksandrowicz, and Auer 2019)(Tabadkani et al. 2019). This represents a significant leap in customization and innovation, yielding buildings that are not only aesthetically unique but also environmentally responsive. Digital Architecture further extends these principles, leveraging digital technologies for design, visualization, and optimization of building performance, including energy efficiency and sustainability (Çetin, De Wolf, and Bocken 2021)(Liladhar Rane 2023).

These modern and contemporary architectural practices demonstrate a profound shift towards dynamic, technology-driven designs prioritizing environmental sustainability and adaptability. This evolution reflects the changing priorities and challenges of our times, where architecture is not merely about aesthetics and functionality but also its impact on the environment and adaptability to changing conditions. Geometry, thus, plays a fundamental role in shaping sustainable design solutions across various architectural paradigms. Table 2.4 provides a comprehensive overview of the crucial role of geometry in various architectural paradigms, emphasizing its significant contribution to the development of environmentally responsible and sustainable architectural practices. This is a general overview of the application of geometry in different paradigms; however, it should be noted that interpretations and applications may vary from one perspective to another.

Considering the escalating concerns surrounding global warming and the concerted effort to mitigate environmental pollution, the construction sector's significant contribution to ecological degradation has garnered considerable attention. Consequently, numerous studies have been undertaken by scholars in various aspects of building design and construction. Architects, in their pursuit of sustainable solutions, have increasingly focused on passive strategies. Among these, determining an appropriate building geometry during the design phase is recognized as a primary passive approach. Table 2-10 shows the history of Geometry Rol in the architectural paradigm.

Architectural Paradigm	Years	Role of Geometry
Bioclimatic architecture	1908-1968	Geometry is utilized to harness climatic resources for thermal comfort, emphasizing sun paths and wind patterns for passive heating and cooling.
Environmental architecture	1969-1972	Geometry serves to minimize ecological disruption, often employing forms that reflect and integrate into the natural surroundings.
Energy conscious architecture	1973-1983	Geometry is employed to reduce energy consumption, focusing on optimizing building forms for energy efficiency and light maximization.
Sustainable architecture	1984-1993	Sustainable architecture leverages geometric design to achieve a balance between environmental responsibility, resource efficiency, and the wellbeing of occupants.
Green architecture	1993-2006	Green architecture incorporates geometric principles to reduce the carbon footprint of buildings, often including the use of renewable energy systems and sustainable materials.
Carbon neutral architecture	2006-2015	Carbon neutral architecture aims for a net-zero carbon footprint, where geometry is applied to maximize renewable energy generation and minimize energy needs.
Regenerative architecture	2016-Future	Regenerative architecture extends beyond sustainability, with geometry playing a role in creating spaces that contribute positively to their environment, aiming for a net-positive impact.

Table 2-11: The history of Geometry RoI in Architectural paradigm, Reference: Author), Appendix D, Page 446

The intersection of geometry and environmental challenges in architecture is increasingly pronounced in the face of rapid urbanization and climate change. As architectural practices evolve, there is a growing recognition of how the geometric design of buildings can significantly impact their environmental footprint (Miao et al. 2022). The application of geometric principles in architecture has evolved from traditional methods of passive environmental control to sophisticated, modern designs that address today's environmental challenges (Altan et al. 2016). Geometry in architecture now serves as a vital tool in creating sustainable, energy-efficient, and environmentally friendly buildings (Shi et al. 2016). This evolution underscores the importance of integrating environmental considerations into every aspect of architectural design, ensuring that buildings of the future are more harmonious with their natural surroundings (Grobman et al. 2023) .

The impact of building geometry has been the subject of extensive research. A review of the literature reveals that most investigations have explored the influence of geometry on environmental pollution, predominantly through the lens of material usage and structural systems. P. Navarro's 2023 research, for example, investigates how various structural parameters like material choice, span, grid options, and building levels impact the environment, aiming to guide designers towards more eco-friendly decisions (Auburtin et al. 2023). Several studies utilize life cycle assessment as a methodology to investigate the carbon footprint caused by material usage in different structural systems or different Geometry (Basbagill et al. 2013) (Płoszaj-Mazurek, Ryńska, and Grochulska-Salak 2020) (Płoszaj-Mazurek 2020)(Speroni et al. 2023)

Moreover, building geometry's influence extends to enhancing living conditions, with energy optimization in architectural design being crucial for sustainability. Dariel Lopes in 2023 underscores the advantages of parametric architecture, which uses algorithmic design for more adaptable and environmentally sensitive solutions (López-López et al. 2023). This approach highlights the evolving nature of architectural design, focusing on material selection and usage in response to environmental challenges. Additionally, A 2022 study by Kistelegdi et al. emphasizes the importance of incorporating energy considerations early in the design process (Kistelegdi et al. 2022). in field of focusing on the impact of geometry on comfort conditions within architectural design, several studies have been conducted. Which delve into how architectural geometry can influence factors such as thermal comfort, lighting, and acoustics within built

environments (Kheiri 2018)(Fedorczak-Cisak et al. 2019) (Ali-Toudert 2009)(Susorova et al. 2013)(Fang and Cho 2019).

Summary:

Amidst escalating concerns about global warming and environmental degradation, the construction sector's contribution to ecological challenges has come under scrutiny, leading to increased focus on passive design strategies. Building geometry is recognized as a primary passive approach, with extensive research exploring its influence on environmental pollution, energy optimization, and comfort conditions within built environments. This literature review highlights the significant role of geometry in addressing sustainable building goals, emphasizing its importance in shaping architectural practices across different paradigms. By leveraging geometric principles, architects can design buildings that optimize natural resources, minimize environmental impact, and enhance overall building performance.

In practice, several strategies have been utilized to harness the potential of geometry in sustainable building design. These include strategic building orientation and layout to maximize solar gain and natural ventilation, utilization of passive solar design principles such as solar shading and thermal mass, incorporation of green roofs and vertical gardens to enhance thermal insulation and reduce urban heat island effect, and implementation of biomimetic design principles inspired by natural geometries for optimal energy efficiency and structural resilience. Additionally, advancements in parametric and computational design tools have enabled architects to explore complex geometries and optimize building forms for enhanced environmental performance. Overall, the integration of geometry into sustainable building design represents a multifaceted approach toward achieving environmental sustainability and resilience in the built environment.

2.8 Energy simulation software and investigating the building's environmental impact

Computer simulation is pivotal for modeling real or hypothetical phenomena within computer programs, aiding in the analysis of system operations. By adjusting variables in these simulations, predictions about system behavior can be made, offering a valuable tool for examining system performance under different conditions. All computer simulations share the goal of creating scenarios for a model where defining various states with distinct initial values is impractical through analytical means due to the complexity and time required.
The evolution of computer software has profoundly influenced building design, enhancing engineering methods and accuracy. Contemporary software facilitates energy analysis of buildings and supports energy management. The identification and manipulation of parameters that affect building energy are essential for reducing consumption and improving the efficacy of energy simulation software. This enables engineers to evaluate, calculate, and develop strategies for energy consumption and optimization in building design and construction.
Life cycle assessment's growing significance in the building sector has spurred software developments aimed at creating prototypes and forecasting the environmental

impacts of buildings. With the extensive array of available software, selecting the most appropriate one is crucial. The choice largely hinges on the research scope, and a comprehensive understanding of each software's capabilities, strengths, and limitations is essential to make an informed selection, optimizing time and resources.
While amid increasing environmental and societal concerns, such as carbon reduction and climate change, the current capabilities of many software platforms are being stretched to their limits. They struggle to provide exhaustive performance analyses of buildings and their environmental control systems amidst the myriad of influencing factors and complex operational conditions. However, the advancement of new building technologies, the necessity for high-performance computation, and the demand for multi-objective models have introduced challenges for building energy simulation software and platforms.

This literature review will explore the application of various building simulation software tools in designing sustainable buildings. These tools can be broadly categorized into two main areas: environmental performance analysis and occupant-centric simulations. Environmental performance analysis tools focus on aspects like energy consumption, daylighting availability, and thermal comfort. Occupant-centric simulations, on the other hand, delve into factors impacting human well-being within the built environment. Recognizing this distinction is crucial for understanding the specific functionalities and advantages offered by each category. Understanding these distinctions enables a more focused and efficacious application in both research and practice. Additionally, the review will examine the integration capabilities of these tools, considering how they interact within a broader computational framework to optimize building performance and sustainability.

In the realm of carbon-mitigation technology within the building sector, building performance simulation (BPS) stands out as a cornerstone, bolstered by the robust support of building energy modelling (BEM) technology. This symbiotic relationship facilitates the realization of energy-efficient designs, operations, and retrofits for buildings. However, the deep integration of multidisciplinary approaches presents both opportunities and challenges for researchers, developers, and practitioners alike. In their 2023 study, Yiqun Pan et al. illuminate the critical role of BPS and BEM in reducing carbon emissions. They underscore the imperative of integrating diverse disciplines while navigating the complexities inherent in applying BEM across various project scales and stages. Through a meticulous review of recent studies, the paper showcases how BEM addresses a myriad of research inquiries spanning different building phases and spatial resolutions. Organizing prevailing research patterns and future prospects into five key areas—performance-driven design, operational optimization, integrated simulation, urban energy planning, and building-to-grid interaction modeling—the study provides valuable insights. Furthermore, it outlines recommendations for future research, advocating for the integration of occupancy and behavior modeling, machine learning, uncertainty quantification, and seamless connectivity with building monitoring systems (Pan et al. 2023).
Building energy modeling has been widely used in the assessment and optimization of building lifecycle performance, and it has considerably contributed to the building sector's energy-efficient, low-carbon objectives. Building energy modeling systems are experiencing new hurdles in terms of capacity, calculability, and compatibility as new building technologies emerge and simulation needs increase. Da Yan et al. developed

DeST 3.0, a new-generation building performance simulation platform, to address the evolving challenges of capacity, calculability, and compatibility in building energy modeling (Figure 2.13). This platform is designed to support the assessment and optimization of building lifecycle performance, contributing to energy-efficient and low-carbon goals in the building sector. DeST 3.0 features four integrated simulation engines: the building analysis and simulation (BAS) engine, the HVAC system engine, the combined plant simulation (CPS) engine, and the energy system (ES) engine, which work together through air and water loop balancing iterations. The platform has been utilized across the entire building lifecycle, offering comprehensive tools for building energy designers, operators, and engineers. DeST 3.0 facilitates reliable, practical, and efficient simulations, supporting diversified and collaborative modeling efforts to enhance building environments and integrate advanced building technologies (Yan et al. 2022). Figure 2-38 shows the application of DeST 3.0 throughout building lifecycle.

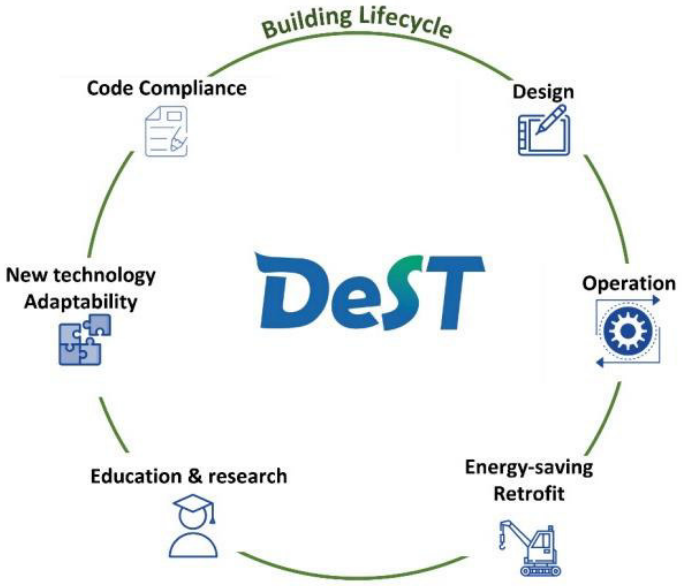


Figure 2-39: Application of DeST 3.0 throughout building lifecycle,

Kunal and Gayatri utilized Autodesk Revit and One-Click LCA to assess the environmental impact of different construction materials in the building sector. Their objective was to compare the environmental effects of concrete and steel frame structures and to analyze the sustainability of traditional versus modern building materials. By adhering to ISO 14040 and ISO 14044 standards for life cycle assessment, they demonstrated that steel frames combined with modern materials have a lower environmental impact than concrete frames with traditional materials (Bonde and Vyas 2023).

Fun BU et al. delved into midday radiative cooling technology as a passive 'zero-energy' solution for building facades. They used DeST, enhanced with a newly developed long-wavelength radiation spectrum integral module (LRSIM), to systematically integrate spectrum-selective radiative cooling into whole-building performance simulations. This approach considered critical factors like atmospheric moisture variation. The integration showcased the tool's strong predictive capability for radiative cooling modeling, offering a comprehensive and user-friendly solution for architects and developers to incorporate radiative cooling technology in buildings (Bu et al. 2022).

Sofie El Din Ahmed and Ahmed Reda conducted a study to develop a methodology for achieving net zero carbon building (NZCB) in hot arid climates, specifically focusing on low residential buildings in the western desert of Egypt. They used Design Builder software for annual simulations and One-Click LCA software for a 50-year life cycle assessment (LCA) to evaluate the carbon emissions and energy consumption of three single-story dwelling models, each with a size of 110 m². Their research aimed to assess the effects of replacing traditional building materials with alternative options and the application of solar panels. The findings indicated that implementing both passive (material substitution) and active (solar panels) strategies led to an 85% decrease in carbon emissions and a 101% reduction in energy usage, highlighting the importance of early adoption of these technologies for achieving net-zero carbon emissions in hot, dry climates (Fouly and Abdin 2022c).

The comprehensive performance evaluation of buildings can significantly influence their initial design. While various methodologies like physical simulation-based, data-driven, and hybrid approaches are extensively available, selecting a single, suitable methodology to yield reliable outcomes often presents challenges. Florio et al. implemented a series of methodologies to iteratively refine the performance evaluation, balancing the advantages and disadvantages of each until a holistic view of the building's performance was achieved. Their study, focusing on a nearly zero-energy building that serves both as living and office space (specifically, the SolAce unit) within the NEST infrastructure in Dübendorf, Switzerland, exemplifies this approach. The overall framework and the specific software utilized for deriving the final results of this study are detailed in Figure 2.14 (Florio et al. 2022).

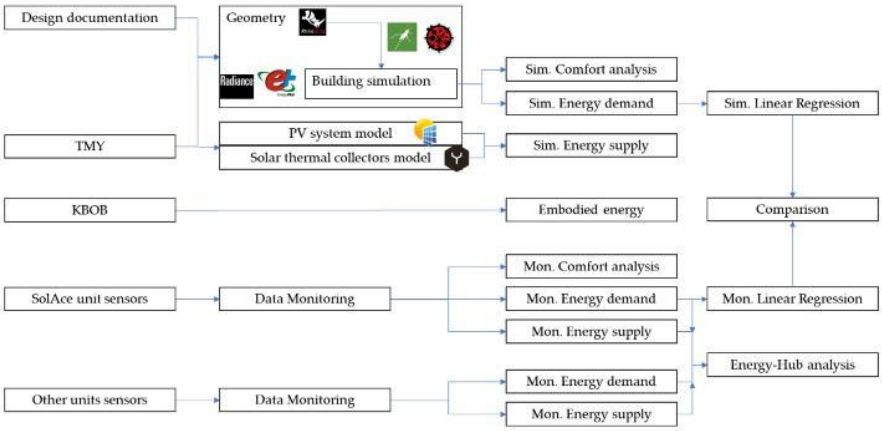


Figure 2-42: Overall methodology workflow (Reference: Florio et al. 2022)

In the field of building energy research, a diverse array of building energy simulation software has been developed, each with its unique advantages and limitations. When considering the use of energy consumption simulation software for buildings, the critical issue is the software's accuracy in predicting actual energy consumption. The choice of software is dictated by the design objectives and necessitates a comprehensive knowledge of each software's capabilities. Challenges in early design stages include frequent design changes, uncertain input variables, and limited design knowledge, which can affect energy-saving potential. Tian Han et al. (2018) explored the practical application of various simulation tools in the early design process, identifying their limitations and the role they play as decision-support tools for specific tasks. Simulation tools were categorized into three groups: design software-based plugins, geometric user interfaces (GUIs) for simulation engines, and standalone simulation tools. The study highlighted that design tools like SketchUp, Revit, and

Rhino have enhanced simulation capabilities through plugins that interface with external simulation engines. Figure 2.15 depicts the foundation for simulation plugins for design tools.

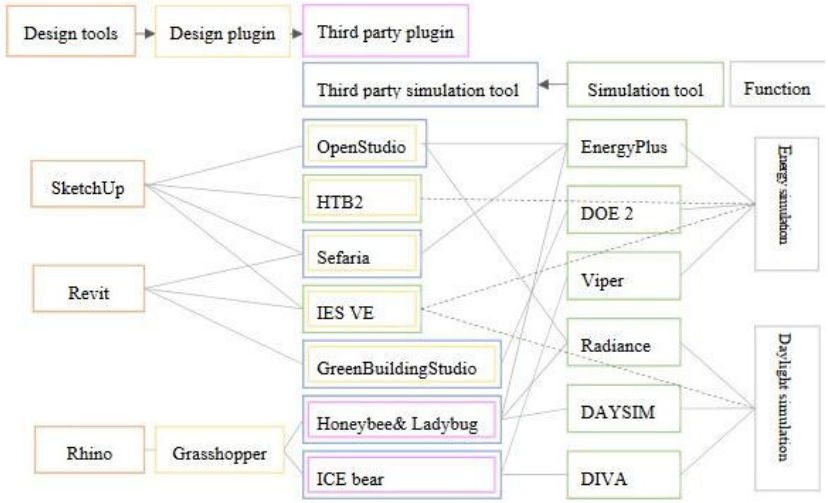


Figure 2-45: The framework of the simulation plugin for the design tool (Reference: T. Han et al. 2018)

Furthermore, GUIs based on simulation engines were examined, emphasizing tools that use established calculation engines to improve functionality and ensure result accuracy. The analysis included a comparative evaluation of these tools, focusing on interoperability, results, and functions, which aids in understanding their utility in building design simulation. Table 2.5 shows the software comparison in interoperability, results, and functions.

	Software		Interoperability			Simulation Results					Functions			Available in the Early Stage
			Design Tool	Simulation Engine	Interoperability	Energy	Thermal	Daylighting	Air Quality	LCC	Carbon Emission	Cloud	UA/SA/PA	Optimization	
plugin		OpenStudio	SketchUp	E+ Radiance	File exchange	√	√	√	√	√			√	√	☆
		HTB2	SketchUp	Own	File exchange	√					√		√		★★
		Sefaira	SketchUp Revit	E+	Run-time	√	√	√				√	√	√	★★
		IES VE	Own Revit SketchUp	Own	File exchange	√	√	√	√	√					★
		Green Building Studio	Revit	DOE2	File exchange	√		√			√	√			★★
	Grasshopper	Honeybee and Ladybug	Rhino	E+/OpenStudio Radiance/DAYSIM	File exchange	√	√	√						√	★
	Grasshopper	IEC bear	Rhino	Viper DIVA	File exchange	√	√	√						√	★
Independent tool		DesignBuilder	Own	E+	File exchange	√	√	√	√	√	√	√	√	√	★
		jEPlus (jESS)	Own	E+	Run-time	√						√	√	√	☆
		N++	Own	E+	File exchange	√	√		√			√			☆
		Virtual Design Studio	Own	E+	File exchange	√	√		√					√	★
		ZEBO	None	E+	File exchange	√	√						√		★★
		Riuska	Own	DOE2	File exchange	√	√		√						☆
		iDbuild	Own	BC/ LC	Standalone	√	√	√	√				√		★
		NewFacades	text	E+	File exchange	√		√							★★
		mkSchedule	SketchUp	E+ Radiance	File exchange	√		√							★★
		MIT advisor	text	Own	File exchange	√	√	√		√		√			★★

Table 2-14: the software comparison in interoperability, results, functions (Reference: T. Han et al. 2018), Appendix D, Page 446

The comparison shows that SketchUp stands out for its extensive range of plugins, indicating its widespread adoption. On the other hand, Revit offers a more integrated platform within the Autodesk suite, facilitating design continuity and cohesive simulation feedback. The Rhino and Grasshopper platforms deserve attention for their

appeal to parametric design within the architectural community, offering flexibility for users to extend functionalities through basic coding. However, these platforms, particularly for beginners, can present challenges due to their developmental stage and potential complexities in usage (Han et al. 2018).

Furthering the discourse on building energy simulation software, Ying Han, Xiao Liu, and Li Chan (2015) provided another comparative analysis of various tools. They delved into the functionalities of key simulation programs like DOE-2 and Energy Plus, examining the features and capabilities of these and other prevalent building energy modeling systems. Their analysis concentrated on the major energy simulation software utilized in China, including DOE-2, Energy Plus, ESP-r, eQUEST, and DeST. The outcomes of their comparison shed light on the performance and appropriateness of these software tools for diverse energy simulation requirements, as elaborated in tables 2.6, 2.7, and 2.9 (Han, Liu, and Chang 2014) .

Table 2-17: Comparison of basic characteristics, Appendix D, Page 447

	DOE-2	eQUEST	EnergyPlus	ESP-r	DeST
Import CAD drawing		√	√	√	
Changeable time step		√	√	√	
Export CAD drawing			√	√	
Output report		√	√	√	√

Table 2-20 :Comparison of calculation capability, Appendix D, Page 447

	DOE-2	eQUEST	EnergyPlus	ESP-r	DeST
Room heat balance calculation		√	√	√	√
Humidity calculation		√	√		√
Heat comfort calculation			√	√	
Nature ventilation calculation		√	√	√	√
Sunlight analysis	√	√	√	√	
Renewable energy calculation		√	√	√	

Table 2-23: Comparison of compatibility, Appendix D, Page 447

	DOE-2	eQUEST	EnergyPlus	ESP-r	DeST
Water cycle calculation		√	√		√
Wind cycle calculation					
Greenhouse gas	√	√	√	√	
Connection with other software			√	√	√

Ghiyae et al. (2015) conducted a comprehensive review and comparison of a wide range of energy simulation software applications in the field of architecture, including DOE-2.1E, BLAST, SUNREL, Bsim, IDA ICE, Energy-10, TRNSYS, Power Domus, Energy Express, Ener-Win, eQUEST, ECOTECT, DeST, Tas, HEED, HAP, EnergyPlus, ESP-r, IES, and TRACE. They initially examined the simulation of energy consumption, functional areas, and specifications of these software tools. Subsequently, the software was compared in terms of efficiency in architectural applications, incorporating John Hansen's survey findings on the use of these tools in American architectural schools to identify the most widely used software. The comparison covered various aspects, including energy calculation cost, weather information integration, reporting outputs, light transmission levels, and general modeling capabilities. Through this comprehensive analysis, Ecotect and eQUEST were highlighted as the preferred software tools in the architectural field, based on their performance across both theoretical and practical evaluations (Ghiyae, M et al,2014).

In 2012, Joana Sousa carried out a comparative analysis of building energy simulation software to assess their capability to handle a wide range of variables and to highlight their differences. She evaluated several tools, including Energy Plus, ESP-r, IDA ICE,

IES-VE, and TRNSYS. The analysis concluded that TRNSYS offered the most comprehensive functionality among the software evaluated. However, the choice of software may vary depending on the user's specific needs and project goals. One notable limitation of TRNSYS was its inability to interface with AutoCAD for file import and export, whereas Energy Plus, ESP-r, and IDA ICE were found to be more compatible in this regard. The comparative details of these software tools were summarized in Table 2.9, illustrating their respective strengths and limitations (Sousa 2012).

	Energy Plus	ESP-r	IDA ICE	IES	TRNSYS
Simulation Solution					
Simulation of loads, systems and solutions	*	*	*	*	*
Iterative solution of nonlinear systems	*	*	*	*	*
Duration of Time Calculation					
Variable time intervals per zone for interaction of the HVAC system	*	*			
Simultaneous selection of building systems and user		*	*	*	*
Dynamic variables based in transient solutions	*	*	*		
Complete Geometric Description					
Walls, roofs and floors	*	*	*	*	*
Windows, skylights, doors and external coatings	*	*	*	*	*
Polygons with many faces	*	*	*	*	*
Imports of building from CAD programs	*	*	*	*	*
Export Geometry of Buildings for CAD software	*	*	*		
Import/Export of simulation models of programs	*	*	*	*	
Calculation of thermal balance	*	*	*	*	
Absorption/release of moisture from the building materials	*		*	*	*
Internal thermal mass	*	*	*	*	*
Human thermal comfort	*	*	*	*	*
Solar Analysis	*				*
Analysis of Isolation	*	*	*	*	*
Advanced fenestration	*	*	*	*	*
Calculations of the building in general	*	*		*	*
Surface temperatures of zones	*	*	*	*	*
Airflow through the windows	*	*		*	*
Driving surfaces	*	*	*	*	*
Heat transfer from the soil	*	*	*	*	*
Thermophysical variable			*		
Daylighting and lighting controls	*	*	*	*	
Infiltration of a zone	*	*	*	*	*
Automatic calculation of coefficients of wind pressure				*	
Natural Ventilation	*	*	*		*
Natural and mechanical ventilation				*	*
Control open of windows for natural ventilation	*	*	*		*
Air leaks in multiple zones	*	*	*		*
Renewable Energy Systems					
Solar Energy	*	*		*	*
Trombe Wall	*	*	*	*	*
Photovoltaic panels	*	*		*	*
Hydrogen Systems		*			*
Wind Energy		*			*
Electrical Systems and Equipment					
Energy Production through R.E.	*	*			*
Distribution and management of electric power loads	*	*			*

Table 2-26: Comparison of features of various simulation software tools (Reference:Sousan,2012), Appendix D., Page 447

Electricity generators	*				*
Network connection	*	*			*
HVAC Systems					
HVAC idealized	*	*	*	*	*
Possible configuration of HVAC systems	*	*	*	*	*
Repetitions cycle air	*	*	*	*	*
distribution systems	*	*	*	*	*
Modeling CO_2			*	*	*
Each distribution of air per area	*	*	*	*	*
Forced air unit per zone	*	*	*	*	*
equipment Unit	*	*		*	*

Hasan Rehman and colleagues focused on advancing toward positive energy buildings (PEBs) by designing and modeling a renewable-based energy system for a genuine demonstration apartment complex in Finland, aiming to produce more energy than it consumes. In their study, they used TRNSYS simulation software for dynamic modeling of the building's energy systems, surpassing the heating, cooling, and plug load demands of the building. The study evaluated the performance of the proposed system by calculating power import and export, life cycle cost (LCC), and onsite energy matching factors. The research provided an in-depth examination of various technologies like photovoltaic thermal systems (PVT), wind turbines, seasonal and short-term buffer heat storage, heat pumps, and district heating/cooling. It also explored their integration with the building, control strategies, types of loads considered in the energy balance, and the definition of building boundaries for calculating this balance, all aimed at helping the building achieve the PEB level sustainably in the Nordic climate (Rehman, Hasan, and Reda 2022b).

Zhaoyun Zeng and Qiong He, in their 2022 study, shifted the focus from specific metrics to a broader approach in assessing the energy-saving potential of bioclimatic buildings, linking it to four key meteorological factors: dry-bulb temperature, wet-bulb temperature, sky temperature, and solar irradiance. Their research proposed a methodology for promptly evaluating the energy-saving potential of bioclimatic structures through these meteorological variables, using building energy simulation. This approach stands out for its ability to connect energy savings with these four meteorological factors, without the need for extensive modeling and simulation of specific measures. Consequently, the methodology is flexible and can be integrated with any Building Energy Simulation (BES) software capable of generating the necessary temperature and energy data, making it adaptable to a wide range of technologies and techniques (Zeng and He 2022).

K. Bataineh and A. Al Rabee (2022) aimed to develop a methodology for identifying optimal energy performance solutions at the lowest cost for residential buildings in the Mediterranean climate. They employed a sequential search optimization method to find cost-effective efficiency packages on the path to zero net energy. Their study involved several steps, starting from establishing a base case reference building, analyzing its structure, thermophysical properties, and user profile, to calculating energy consumption and identifying energy-saving measures. Design Builder (DB), powered by the Energy Plus simulation engine, was used to test these energy conservation methods. DB's strengths include extensive geometry input options, a broad material library, and detailed load profiles, enabling a comprehensive analysis of the building's HVAC and lighting systems. This analysis helped assess the effectiveness of various energy conservation measures (ECMs) in maintaining thermal comfort while reducing energy use (Bataineh and Al Rabee 2022). Figure 2-16 shows a summary of this methodology.

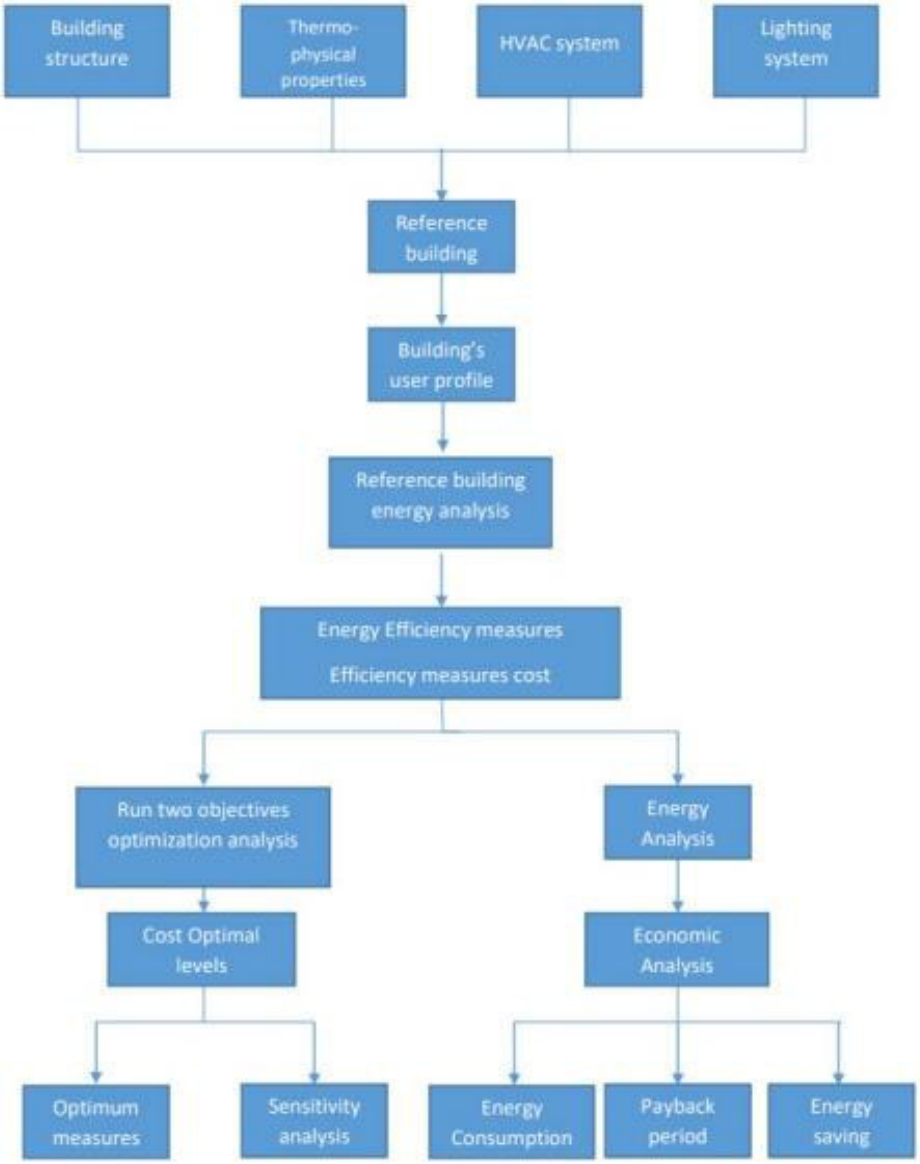


Figure 2-48: Methodology flow chart for determining cost-optimal efficiency packages(Reference: Bataineh and Al Rabee 2022)

In the study by C. Heracleous et al. (2022), a methodology was proposed to evaluate energy-demand savings and cost-effectiveness of retrofit measures in educational buildings in Cyprus, focusing on long-term cost efficiency. The study utilized Integrated Environmental Solutions (IES-VE) for dynamic software simulation to model energy demand and assess retrofit options through life cycle cost analysis (LCCA). The findings highlighted that the most effective energy-saving measure was the installation of mechanical ventilation with heat recovery, leading to a 49% reduction in primary energy use. Roof insulation followed with an 18% reduction, and wall insulation with a 9% reduction. Other measures like increasing overnight ventilation rates, upgrading windows, and adding shading devices to south-facing classrooms had minimal impact on energy efficiency. The combined retrofit scenarios showed potential energy demand reductions of 62% to 77% for the analyzed educational building (Heracleous et al. 2022).

Shuai Zhang and colleagues focused on energy conservation in small public buildings, emphasizing the significance of the envelope system in reducing energy consumption. In their research, they employed the COMSOL multi-physics simulation program to conduct a two-dimensional simulation study on the heat transfer characteristics of the community center's external envelope. This analysis was aimed at quantifying the energy-saving potential of the building's outer envelope construction (Zhang, Sun, and Sun 2022).

In their 2022 study, Hongzhi Zhu et al. concentrated on enhancing the efficiency of solar absorption refrigeration systems using phase change materials. They specifically investigated a lithium bromide-water absorption refrigeration system in Taiwan, employing the TRNSYS transient simulation software to model the system's performance both with and without phase change materials. This approach was aimed at overcoming the limitations of traditional solar absorption refrigeration systems, such as low solar energy utilization and poor intermittent performance. The simulation results indicated that integrating phase change materials into the system resulted in a 4.2% increase in collector efficiency, demonstrating the effectiveness of TRNSYS in evaluating improvements in solar refrigeration technologies (Zhu et al. 2022).

Abdelkader Sarri and colleagues conducted a study in 2021 that employed simulation-based optimization using Energy Plus and GenOpt tools. Their research aimed to find the optimal melting temperature for phase change materials (PCMs) when integrated into the building envelope, focusing on their thermal performance in both shaded and unshaded lightweight constructions across various Algerian climate zones. The study highlighted the potential of PCMs as a passive design strategy to enhance building energy performance. The optimization results indicated that, particularly in hot-dry climates, the PCMs could achieve modest cooling energy savings for mechanically ventilated buildings during summer, with the ideal melting temperatures being 28 °C or higher (Sarri et al. 2021).

Venu Shree and colleagues, in their 2021 study, focused on estimating the carbon footprint of an academic building in India. They utilized the Life Cycle Assessment (LCA) technique within GaBi education software to calculate the carbon emissions generated by various activities associated with the building, including resource usage, transportation, and utility operations. The study aimed to identify carbon-intensive processes and compare different systems and processes. Following the carbon footprint assessment, they proposed remedial measures to reduce the building's carbon footprint and enhance its sustainability. The findings highlighted the significance of a building's location in determining its emission levels, as longer transit distances can increase emissions. Additionally, it was noted that academic buildings tend to have lower resource consumption and associated emissions compared to residential buildings, likely due to their limited operational hours, primarily during the day (Shree, Nautiyal, and Goel 2021).

Summary :

Various building simulation software tools are available for analyzing energy usage, daylighting, climatic conditions, and environmental analyses in sustainable building design. Researchers have utilized software such as Autodesk Revit, One-Click LCA, Design Builder, TRNSYS, Energy Plus, and others for energy performance analyses, life cycle assessments, and optimization of building designs. Studies have compared the capabilities and effectiveness of different simulation software, highlighting their

features, limitations, and suitability for various research objectives. Building simulation software contributes significantly to energy-efficient designs, operations, and retrofitting, aiding in carbon-mitigation efforts within the building sector. Challenges include selecting the most appropriate software for specific research needs and considering factors such as accuracy, versatility, integration capabilities, and ease of use. Integration of multidisciplinary approaches and advanced technologies like machine learning and digital twin models further enhance the effectiveness and applicability of building simulation software.

Building simulation software plays a crucial role in achieving energy-efficient and sustainable building designs. To select the best software for research purposes, researchers should consider several factors:

- Accuracy and reliability of the software in predicting energy consumption and environmental impacts.
- Versatility and integration capabilities to address diverse research objectives and project scales.
- Ease of use and accessibility for researchers with varying levels of expertise.
- Compatibility with other tools and technologies for seamless integration and data exchange.
- Support for advanced features such as machine learning, digital twin models, and uncertainty quantification.

By carefully evaluating these factors and conducting comparative analyses of available software options, researchers can choose the most suitable building simulation software to advance their research goals and contribute to the development of energy-efficient and sustainable building practices.

2.9 Conclusion

Throughout the history of architecture, geometry, and materials have played a fundamental role in shaping buildings and addressing environmental challenges. From bioclimatic design to the pursuit of positive buildings, these passive solutions have been consistently employed by architects seeking to improve energy efficiency, thermal comfort, and minimize environmental impact. Today, the goal of achieving positive buildings – structures that generate more energy than they consume and actively contribute to ecological health – demands a holistic and integrated approach.

Successful design of positive buildings necessitates a comprehensive framework that guides the process. This framework must prioritize the following:

Strategic Geometry: Optimizing building form and orientation to harness natural energy sources, regulate temperature, and enhance natural ventilation. Exploration of biomimetic principles can yield innovative and sustainable geometric solutions. For instance, designing buildings with shapes inspired by natural phenomena such as the honeycomb structure of beehives or the branching patterns of trees can maximize structural efficiency and energy performance.

Eco-conscious Materials: Prioritizing sustainable, recycled, upcycled, non-toxic, and low-embodied-carbon materials throughout the building's lifecycle. Utilizing materials such as recycled steel, reclaimed wood, and low-impact concrete can significantly reduce the environmental footprint of construction while promoting circular economy

principles. Additionally, incorporating innovative materials like photovoltaic-integrated glass facades or self-healing concrete can enhance the energy efficiency and longevity of positive buildings.

Integrated Design: Seamless collaboration between architects, engineers, energy specialists, and other stakeholders from the earliest stages of design to ensure optimization across all systems. Integrated design processes facilitate the holistic consideration of building performance metrics, allowing for informed decision-making regarding geometry, materials, energy systems, and overall building performance. This interdisciplinary approach fosters synergy and innovation, leading to more efficient and sustainable building solutions.

Simulation Software: Advanced simulation software like EnergyPlus, DesignBuilder, and OpenStudio aid architects in optimizing building performance for energy efficiency and sustainability. These tools allow for detailed analysis of design choices, material impacts, and energy systems, including energy consumption, thermal comfort, daylighting, and air quality. Additionally, environmental assessment tools like OpenLCA, One Click LCA, and Athena Impact Estimator help architects quantify the environmental impact of construction materials and processes throughout a building's life cycle.

While a robust framework is essential, it must remain adaptable to accommodate technological innovations. Emerging areas such as AI-driven energy management and advanced materials hold great promise in revolutionizing positive building design. AI-powered building management systems can optimize energy consumption, improve occupant comfort, and reduce operational costs by learning and adapting to occupant behavior and environmental conditions in real time. Additionally, advancements in materials science, such as the development of nanomaterials, bio-based composites, and carbon-negative construction materials, offer exciting opportunities to further enhance the sustainability and performance of positive buildings.
The transition to positive buildings represents a crucial step in addressing the climate crisis. By embracing both time-tested passive solutions and cutting-edge technologies, architects have the power to create a built environment that not only sustains but actively regenerates our planet. Through strategic geometry, eco-conscious materials, integrated design processes, and advanced simulation tools, architects can design and construct buildings that serve as models of sustainability, resilience, and innovation, contributing to a healthier and more sustainable future for generations to come.

CHAPTER 3

Research Methodology, Strategy, Guidelines & Contribution in Boston Research Experience

3.1 Abstract

The methodology chapter focuses on describing the research design, methods, and procedures used to conduct the study. It provides a comprehensive explanation of how the data was collected, the tools or instruments utilized, and the overall approach to conducting the research. The purpose of this chapter is to offer an overview of the research process, ensuring the transparency and reproducibility of the study. In this thesis, the researcher determined the scope and framework of the study after a thorough review of the existing literature and related research. Focusing on the regenerative design framework as the latest paradigm in environmental architecture, this thesis employs life cycle assessment as a quantitative analysis tool and for hypothesis testing. In this regard, the chapter defines the concepts, introduces the modelling application software, and outlines the required documents. Additionally, the researcher specifies the specific fields related to the research and defines the necessary terms for the modeling process. Ultimately, this chapter lays the groundwork for the next modeling chapter by clearly outlining the methodological approach, thereby facilitating a deeper understanding and interpretation of the research findings.

In the upcoming chapter, the research methodology will delve into various key topics essential for conducting the study effectively. These topics include:

Regenerative Design: Exploring the principles and methodologies of regenerative design within the context of environmental architecture.

Life Cycle Assessment (LCA): Understanding the application of LCA as a quantitative analysis tool for evaluating the environmental impacts of products and systems throughout their life cycle.

Environmental Product Declarations (EPDs): Examining the concept of EPDs and their role in providing transparent and comparable information about the environmental performance of products.

Product Category Rules (PCRs): Defining PCRs and their importance in establishing consistent and reliable guidelines for conducting life cycle assessments within specific product categories.

Leadership in Energy and Environmental Design (LEED): Discussing the LEED certification system and its criteria for evaluating the sustainability performance of buildings.

Building Research Establishment Environmental Assessment Method (BREEAM): Exploring the BREEAM framework and its approach to assessing the environmental performance of buildings.
Building Simulation Software: Introducing various simulation tools used for analyzing and predicting the performance of building designs.
These topics will form the foundation of the research methodology, guiding the approach to data collection, analysis, and interpretation throughout the study.

3.2 Regenerative Design

The publication of the 2013 Intergovernmental Panel on Climate Change (IPCC) report marked a pivotal moment, highlighting the limitations of efficiency-based approaches in addressing environmental challenges. This realization has garnered widespread scientific and public recognition. Consequently, research and studies across various disciplines, including architecture, have shifted their focus toward identifying more practical solutions for environmental problems.
This paradigm shift is evident in the emergence of "ultra-efficiency" and "effectiveness" as guiding principles within architecture and construction. These new paradigms challenge traditional, linear thinking regarding resource consumption. For nearly four decades, the dominant paradigm has emphasized "Reduced Negative Impact through Enhanced Efficiency." However, in the face of the escalating environmental crisis, this approach has proven inadequate. A new paradigm is needed, one that transcends mere mitigation and instead fosters "Increased Positive Impact through Enhanced Regenerative Effectiveness." This necessitates a shift from simply maintaining human societies and ecosystems to actively promoting their recovery and regeneration.



Figure 3-1:
Paradigm shift towards a beneficial positive impact footprint of the built environment,(Der Heijden Robert et al. 2017)

The next two decades are expected to usher in the seventh paradigm: regenerative architecture (Attiya 2018). This paradigm draws inspiration from the earlier works of Lyle (1996a) on regenerative design, Braungart and McDonough (2010) on cradle-to-

cradle principles, and Benyus (2002) on biomimicry. While promising, this shift necessitates a strong commitment to integrating regenerative and cyclical approaches into architectural practice(Der Heijden Robert et al. 2017). (Figure 3.1)
By strategically defining materials within biological and technical cycles, buildings can be designed to actively enhance biodiversity, air quality, and water quality while generating surplus energy. Buildings can function as repositories of valuable materials, fostering a circular economy where resources are perpetually reused. This strategy lies at the heart of designing positive-impact buildings. To accelerate progress, clear and actionable definitions are needed to catalyze innovation in creating regenerative and circular structures that positively impact people, the planet, and the economic.
The regenerative paradigm offers the potential to reverse the detrimental effects of climate change within the framework of the existing capitalist system (Pediaditakis 2021). This approach fosters a deeper understanding of materials and embodied energy, promoting responsible selection and challenging the limitations of reductionist design methodologies. Regenerative architecture holds the key to creating buildings with beneficial footprints and positive impacts, aligning with the goals of the United Nations Framework Convention on Climate Change.
Regenerative design and sustainable development share the aspirational goal of creating a world that promotes diversity, health, justice, ecological harmony, and the responsible use of resources like water, soil, air, and energy. Over the past decade, significant advancements have been made in measuring and quantifying the environmental impacts of the building sector. The growing importance of Environmental Product Declarations (EPDs), which provide detailed life cycle assessments of building materials, exemplifies this progress.

3.2.1 Guidelines Principles

Currently, several key frameworks and standards guide sustainable architecture:

a) Holistic Building Rating Systems: Examples include LEED, BREEAM, Living Building Challenge, and DGNB, which offer comprehensive assessments of sustainability.
b) Specialized Building Standards: Standards such as Passive House and Active House focus on achieving specific performance targets related to energy efficiency and comfort.
c) Product and Material Labels: EPDs and the Cradle-to-Cradle (C2C) Certified Product Standard promote transparency and guide the selection of environmentally responsible materials.
Research aligned with regenerative principles has identified five core tenets derived from the C2C Certified Product Standard (MBDC 2014). This internationally recognized label evaluates products and materials based on the table 3.1:

Five major guidelines principles based on the cradle to cradle				
Material Health	Material Reutilization	Renewable Energy and Carbon Management	Water Stewardship	Social Fairness

Table 3-2: Five guiding principles based on the cradle to cradle

As one of the most progressive approaches to product design, the C2C concept actively encourages regenerative practices by promoting upcycling and maximizing the residual value of products throughout their lifecycle.

3.2.2 Framework for Regenerative Design

A robust architectural foundation is essential for successful regenerative design paradigms (Attia, 2011, 2015, 2016a, b, 2017). Such a framework provides architects with a structured methodology to conceptualize and evaluate projects that yield positive, regenerative outcomes. It facilitates the systematic planning and management of design processes, ensuring that buildings deliver net beneficial impacts. This framework acts as a guide for the selection, integration, and configuration of adaptable structural systems, architectural elements, and regenerative building materials.

The foundational principles of regenerative design can be operationalized into a framework that assists architects in making critical design choices during the initial phases of a project. Guided by a rigorous thought process, the five core tenets of regenerative design – safe and healthy materials, material reuse, renewable energy and carbon stewardship, water conservation, and social equity – must be translated from abstract concepts into tangible architectural strategies. This framework emphasizes three primary tactics. These Three design methods form the foundation of the regenerative design framework. The idea development phase should begin with the use of these three essential tactics, and they will be employed throughout the design process. By using the next three tragedies, a design thinking paradigm will be introduced, one that incorporates sustainability naturally into the design process. (Amherst and Littman 2014) (Diagram 3.1).

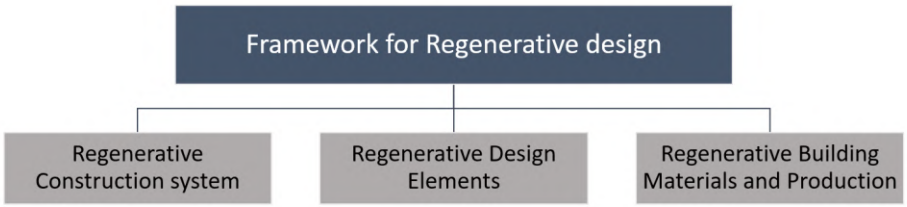


Diagram 3-2: Strategies for Regenerative Design,(Amherst and littman,2014), Appendix C, Page 393

3.2.2.1 Regenerative Construction

As an initial design strategy, architects and engineers should prioritize a flexible construction system that integrates both architectural design elements and sustainable products. Such a system is crucial for facilitating future alterations of buildings, including the addition, removal, or substitution of envelope and façade components. Key considerations include:

Constructive and Structural Choices: Selecting a rational configuration of structural elements (e.g., columns, beams, and slabs) is essential to enhance the lifecycle and adaptability of the building components.

Flexibility of the System: A flexible construction approach simplifies the disassembly process, promoting the salvage, enhancement, alteration, or repurposing of building materials.

Modular Design: This approach enhances the versatility of building functions and facilitates the reutilization of components and materials, contributing to a more sustainable construction practice.
Structural Optimization: Employing minimal materials to achieve the maximum load-bearing capacity of the structure is vital for resource efficiency.
Material Selection: Prioritizing materials based on both quantity and quality with an eye towards environmental sustainability (including reuse, recycling, and upcycling capabilities) can significantly reduce construction waste and environmental impact. This selection process should align with the principles of regenerative design to maximize the potential of the spatial structure within the chosen construction system strategy (Sadafi, Zain, and Jamil 2014) (Mang and Reed 2020)
By adopting these strategies, building design can evolve to be more sustainable, adaptable, and environmentally responsible.
The building system should facilitate the architectural, spatial, and technological transitions between the interior and exterior environments. Once a flexible construction method is established, the design team should concentrate on the entire structure to finalize the project's mass, plans, and layout. Diagram 3.2 presents a summary of the guidelines for the initial methodology of regenerative design.

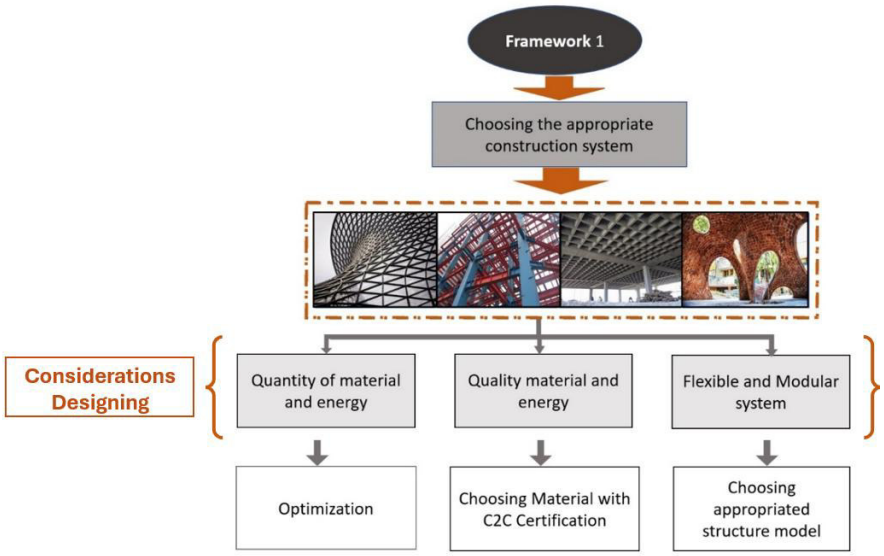


Diagram 3-5: first framework for regenerative design, (reference: Author),Appendix C, Page393

3.2.2.2 Regenerative Design Elements

Architectural design plays a pivotal role in shaping buildings that align with regenerative goals. By integrating passive design strategies, often inspired by the wisdom of traditional vernacular architecture, architects can create spaces that offer enhanced interior thermal comfort while minimizing environmental impact.

Once the construction system is selected, the importance of architectural design is emphasized through the strategic design of elements. Incorporating passive solutions in the architectural design process, a practice rooted in historical precedent enables the integration of traditional architectural insights to enhance interior comfort for users. The appropriateness of specific elements may vary based on geographical and climatic conditions, ensuring architectural integrity (Moossavi 2014).

Climatic design solutions include atriums, courtyards, terraces, balconies, skylights, glazed facades, staircases, meeting rooms, open office spaces, common areas, foyers, and roof gardens. Learning from traditional to climatic design involves recognizing climatic potentials and tailoring designs to climate conditions, a practice often overlooked in modern rapid development. Historically, there was significant knowledge of renewable energy use in architectural design, notably in passive solar architecture and passive systems for cooling, heating, and ventilation. Reengaging with these traditional methods can help reduce environmental pollution and enhance indoor thermal comfort in vernacular buildings (Pilechiha et al. 2022).
. Designing for climate acts as a primary defense against external environmental factors, necessitating the application of passive design principles, energy-efficient heating and cooling systems, and energy-efficient occupant behavior (Javanmard, 2022).
The relationship between construction projects and climate encompasses two main aspects:

1- The impact of climate on the design, shape, and placement of buildings.
2- The direct influence of climate on construction processes.

In this context, the following should be considered:

- Selecting an appropriate and optimal location.
- Arranging buildings in a way that considers their interaction with each other and with climatic elements.
- Using materials that are resistant to climatic factors.
- Designing the building's plan, shape, and architecture to accommodate climate conditions.
- Establishing comfort indices based on climate-compatible architecture.

Therefore, at this stage, it is critical to consider various factors such as air quality and human health, energy savings, renewable energy production, water management, and designing with nature. Architects should implement both passive and active solutions. Passive solutions include designs inspired by and based on nature.
The ability to synchronize design elements with the construction system, achieving multiple architectural and building performance goals, will influence the definition of design elements. At this point, it is essential to identify and quantify the architectural design components most likely to positively impact a project. Assessing the technical and geographical feasibility of incorporating regenerative design elements should be conducted using an appropriate scale. More importantly, these elements should be aligned with future performance metrics and objectives. Diagram 3.3 illustrates the summary of the second guideline methodology for regenerative design. It is imperative for each project to incorporate regenerative elements to enhance the quality of the architectural experience.

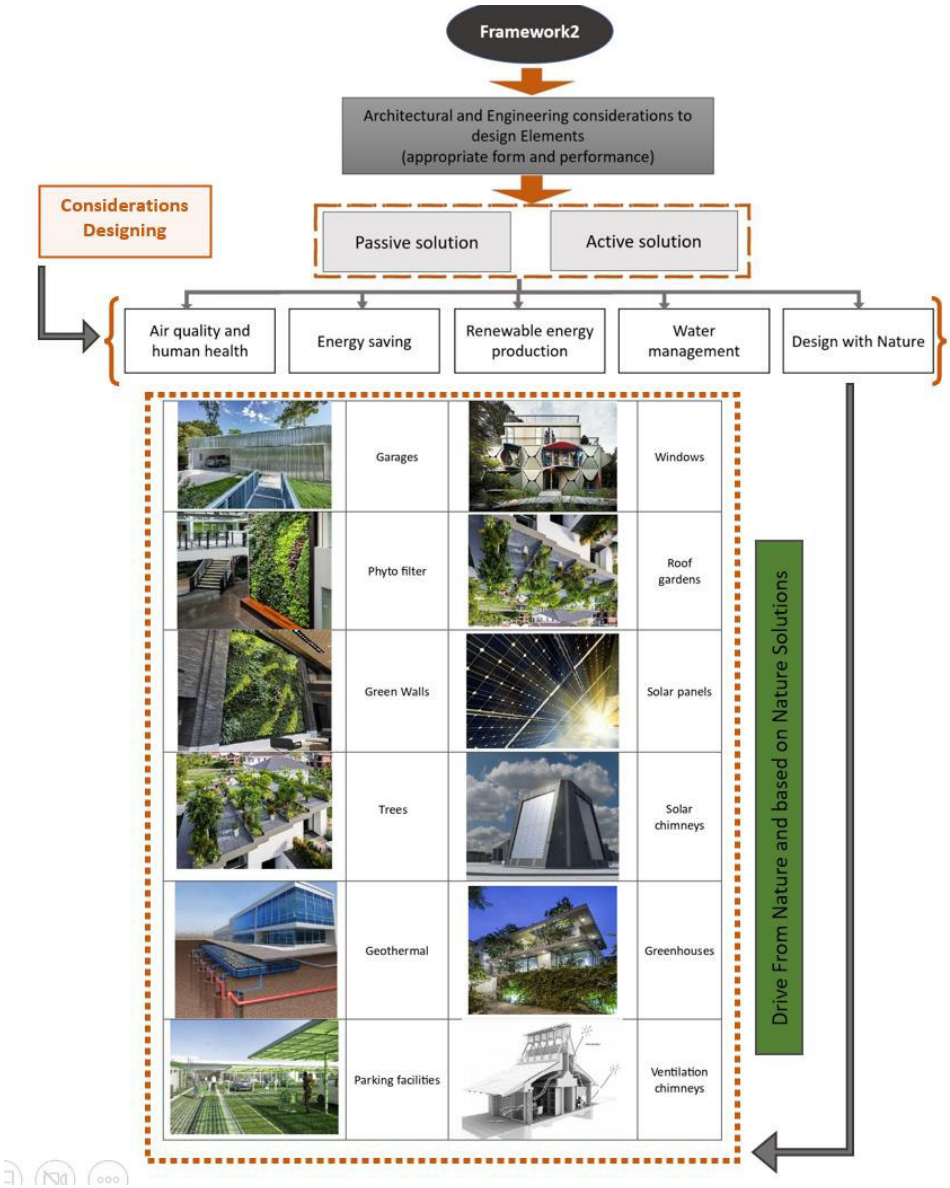


Diagram 3-8: second Framework for regenerative design (Photo's References:www.archdaily.com), Appendix C, Page 394

3.2.2.3 Regenerative Materials

Selecting appropriate materials is one of the most critical—and challenging—decisions in the construction process, given their environmental impacts across their lifecycles. These lifecycle stages include raw material acquisition, materials manufacture, production, use/reuse/maintenance, and waste management. Designers must thoroughly understand the environmental effects of various material types to make informed choices. Materials can be categorized into groups such as intelligent materials, biological, reusable, and recyclable. Regardless of the category, the use of regenerative materials must not compromise quality (Buckton et al. 2023).

Sustainable Materials Management (SMM) advocates for the productive use and reuse of materials throughout their entire lifecycles, promoting a shift in societal views on natural resource utilization and environmental protection. An SMM approach aims to maximize material efficiency, minimize toxic substances, and mitigate environmental impacts during the material's lifecycle, ensuring resource sufficiency(Pontius and McIntosh 2024).
Life Cycle Assessment (LCA) serves as a tool to comprehend the broader human health and environmental ramifications of products, processes, and activities, evaluating air, water, land, and energy implications, alongside potential alternatives. Materials with Environmental Product Declarations (EPD), Cradle to Cradle (C2C) certifications, or other eco-certifications should align with regenerative design principles. Attention must be paid to fire safety, embodied energy, carbon content, and the structural, mechanical, hygrothermal, and acoustic properties of materials. Preference should be given to biosphere-friendly materials like clay, wood, straw, bamboo, or hemp when possible. Technological materials that facilitate disassembly and reuse, are certified or have EPDs, exclude toxic chemicals, and minimize environmental production impacts are recommended.

3.2.3 Enhancing Knowledge in Regenerative Design Through Boston-based Collaborative Experience

During my tenure in Boston, I conducted in-depth site visits and analyses of several exemplary buildings known for their regenerative design principles. Notable among these are the Massachusetts Institute of Technology's (MIT) E62 building and the Boston University Center for Computing & Data Sciences. These structures demonstrate advanced regenerative design strategies, including the integration of renewable energy systems, efficient water management practices, and the utilization of sustainable building materials.

3.2.3.1 Massachusetts Institute of Technology's (MIT) E62 building (Boston)

The E62 building at MIT is part of the Sloan School of Management and is known for its sustainable design features. Completed in 2010, it has achieved LEED Gold certification, reflecting its commitment to environmental sustainability. The building incorporates a high-performance envelope with operable windows for natural ventilation, a partial green roof, low-wattage lighting, demand ventilation, occupancy sensor controls, and water-based terminal heating and cooling units. Additionally, it offers easy access to usable outdoor spaces, enhancing its environmental credentials. The E62 building employs green roofs and rainwater harvesting systems, which enhance its sustainability profile.

E62 Building's Sustainable Design Features:

Green Roofs and Rainwater Harvesting: The E62 building features green roofs that help manage stormwater, reduce the urban heat island effect, and provide insulation. Rainwater harvesting systems further contribute to its sustainability.

Energy Efficiency: The building employs passive solar design and advanced insulation techniques to minimize energy consumption. Sunshades and screens on the southern façade improve daylighting while reducing solar heat gain.

Daylighting and Lighting Controls: The use of daylighting controls on lighting and window shades helps reduce energy use, ensuring that artificial lighting is only used when necessary.





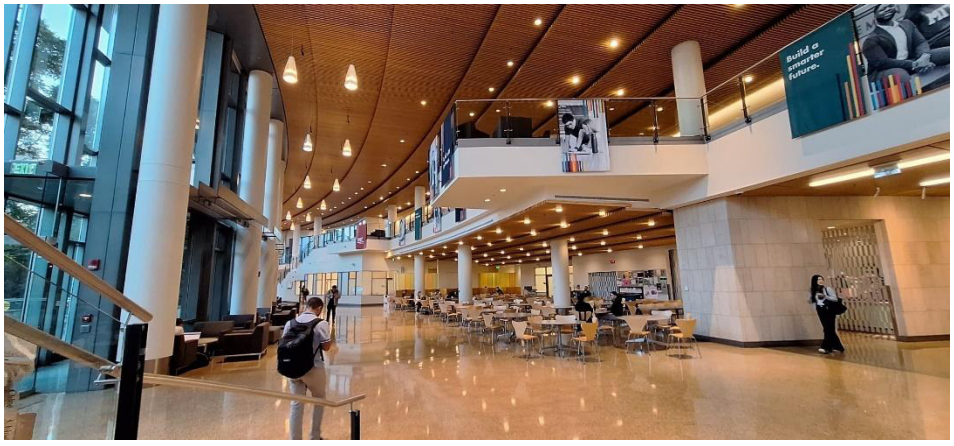




Figure 3-4: MIT E62 Building, (Reference: Author)

These features not only make the E62 building a model of sustainable design but also provide practical examples of regenerative design principles in action. Observing these implementations has greatly informed my understanding of how such principles can be applied in urban environments, enriching the methodological framework of my thesis on regenerative design. Figure 3.2 shows the E62 building.

3.2.3.2 The Center for Computing & Data Sciences at Boston University

The Center for Computing & Data Sciences at Boston University is a cutting-edge facility designed to foster innovation and collaboration in the field of data science. It incorporates passive solar design and state-of-the-art insulation techniques to minimize energy consumption. Engaging with these projects allowed for a comprehensive examination of practical implementations of regenerative design in urban settings. The firsthand observations and detailed evaluations of these buildings provided critical insights into the operationalization of regenerative design concepts, thereby significantly enhancing the methodological framework of this thesis. This experiential learning underscored the practical viability and transformative potential of regenerative design in promoting sustainable and resilient built environments (Fugure 3.3).



Figure 3-7: The Center for Computing & Data Science at Boston University, (Reference : Author)

Sustainable Features of the Center for Computing & Data Sciences at Boston University:

Sustainable features in information technology (IT) focus on reducing environmental impact and enhancing efficiency. Here are some key sustainable IT features:

Reduce E-waste: Implementing programs to recycle and responsibly dispose of electronic devices can significantly reduce e-waste and its environmental impact.

Energy Efficiency: Utilizing energy-efficient hardware and optimizing data center operations to reduce energy consumption is crucial. This includes using low-power servers and optimizing cooling systems.

Green Software Development: Developing software that optimizes resource usage and reduces the computational load can contribute to IT sustainability.

Cloud Computing: Measuring and managing the carbon footprint of cloud services helps in minimizing the environmental impact of IT infrastructure.

Renewable Energy Integration: Powering data centers and IT infrastructure with renewable energy sources, such as solar or wind, supports sustainability goals.

Sustainable Materials: Using sustainable, natural materials in the production of IT equipment can reduce the overall environmental footprint.

These features help create a more sustainable IT environment, reducing the ecological footprint and promoting long-term environmental health (Figure 3.4).



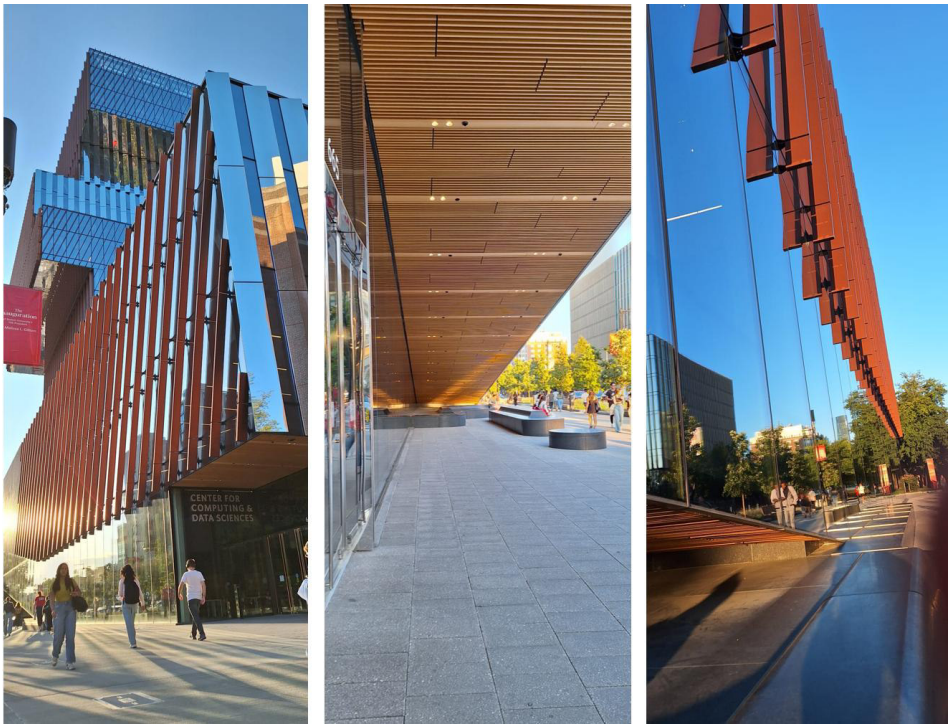


Figure 3-10: The Center for Computing & Data Science at Boston University, (Reference Author)

3.3 Life Cycle Assessment Method

Buildings are responsible for one-third of global greenhouse gas emissions and nearly 40% of the world's energy consumption, which is substantially higher than that of transportation. Energy is used throughout the following processes: producing building materials, moving those materials from manufacturing facilities to construction sites, constructing the building, running it, and demolishing the structure (and, if appropriate, recycling its components) (Vigovskaya et al., 2018)

The studies indicate that over 80% of greenhouse gas emissions from buildings occur during their operational phase, primarily due to energy consumption for heating, ventilation, cooling, lighting, appliances, and other operational activities. Assessing and quantifying the environmental impacts of buildings necessitates a comprehensive approach that encompasses all stages of a building's life cycle, from initial construction to eventual demolition, a concept often referred to as "cradle to Cradle." Life Cycle Assessment (LCA) provides a robust framework for this analysis, thereby forming the basis of this research, which focuses on environmental pollution from buildings during their use phase.

In this context, the researcher has conducted a thorough review of the Life Cycle Assessment methodology as part of the research framework. The objective is to gain a deeper understanding of how LCA can be effectively applied to evaluate the environmental footprint of buildings throughout their life cycle. By doing so, the study aims to identify sustainable practices and methods that can reduce the overall

environmental impact of buildings, particularly during the usage stage where the majority of emissions occur. This comprehensive approach to LCA serves as a critical tool in the sustainable design and operation of buildings, ensuring that environmental considerations are integrated throughout the building's life span.

3.3.1 Enhancing Life Cycle Assessment Knowledge Through Boston-based Collaborative Experience

During my time in Boston, particularly at Northeastern University under the mentorship of Dr. Matthew Eckelman, I gained invaluable insights into life cycle assessment (LCA). The collaborative environment and exposure to cutting-edge research significantly enriched my understanding of how LCA principles can be effectively applied in architectural design. Engaging with a diverse group of researchers allowed me to explore innovative methodologies and technologies that enhance the accuracy and comprehensiveness of sustainability assessments.
This experience deepened my knowledge of integrating LCA into the design process, emphasizing the importance of evaluating both environmental and economic impacts across the entire lifecycle of building materials and systems. The practical applications and case studies encountered in Boston have profoundly influenced the development of my thesis, providing a robust foundation for proposing advanced LCA strategies that can be adapted to various contexts and scales. This has ensured that my methodological framework is robust, comprehensive, and aligned with the latest advancements in sustainable design practices. The insights gained from this experience have equipped me with the tools to critically assess and optimize the sustainability of built environments, thus contributing to the broader goals of environmental stewardship and climate resilience. The following section highlights some of my achievements after completing the course titled "Life Cycle Assessment" and the results of studying this method, and how it has impacted my methodology.

3.3.2 LCA Background

Stated in the study of LCA history, the German term "Ökobilanz," meaning "ecological balance," was initially utilized in a study by the Environmental Confederation Agency of Switzerland. This term had a significant influence, particularly in German-speaking countries, leading to the English equivalent, Life Cycle Assessment (LCA).
In the introductory part of the International Standard ISO 14040, which serves as a framework, LCA is defined as follows: "A life cycle assessment (LCA, also known as life cycle analysis, Eco-balance) is a technique for assessing the environmental aspects and impacts related to a product, covering all stages from cradle-to-grave (i.e., from raw material extraction through materials processing, manufacture, distribution, use, repair, maintenance, and disposal or recycling)."
The LCA methodology, dating back to the 1960s and early 1970s, focused on energy efficiency, raw material consumption, and waste disposal. In 1969, Coca-Cola conducted one of the first LCA studies to compare resource consumption and environmental releases of beverage containers. In Europe, a parallel approach called "Ecobalance" was developed. Ian Boustead, in 1972 in the UK, calculated the total energy used in producing various types of beverage containers and later published the "Handbook of Industrial Energy Analysis" in 1979 (Vigovskaya, Aleksandrova, and Bulgakov 2017).

Although interest in LCA continued, it expanded significantly in the mid-1980s to early 1990s across various sectors. In the early 1990s, LCA started being used for external objectives, like marketing (D.Elcock, 2007). The Society of Environmental Toxicology and Chemistry (SETAC) adopted a similar definition of LCA in its 1993 "Code of Practice."
Such definitions are also present in the DIN-NAGUS guidelines and the "Nordic Guidelines," authorized by Scandinavian Ministers of the Environment. The history and key components of LCA are summarized in various documents and guidelines.

Life Cycle Assessment (LCA) is a comprehensive method for evaluating the environmental and resource impacts associated with the entire life cycle of a product or system, traditionally focusing on the ecological aspects of sustainability. This analysis spans from raw material extraction (cradle) through production, transportation, usage, and eventual disposal or recycling (grave), encompassing all significant stages such as material and product manufacturing, use, and end-of-life management. The concept of "cradle to grave" ensures that every critical phase in a product's life cycle is included in the assessment, which covers the extraction of raw materials from the environment (soil, water, air), material and final product production, usage, and waste management, including recycling. Transportation involved in these stages is also considered.
Traditionally, LCA limited its scope to environmental impacts to avoid methodological overload, excluding economic and social factors from the analysis. However, as the field of sustainable product development has evolved, there is a growing recognition of the importance of integrating these factors into the LCA process. This integration reflects a broader understanding of sustainability that encompasses not just environmental, but also economic and social dimensions, leading to a more holistic approach to assessing and improving the sustainability of products and systems. The development of LCA has been documented historically, showing its evolution from a purely ecological assessment to a more integrated sustainability evaluation tool. The advancement in LCA methodology is increasingly aligned with the sustainable development goals, which advocate for a balanced approach to ecological, economic, and social impacts. This evolution underscores the necessity for a "cradle to cradle" approach, where the end-of-life phase of a product is considered not as waste but as a resource for new production cycles, thereby promoting a circular economy. The term 'products' in LCA encompasses both goods and services, with the latter requiring the same consideration for process and energy use as tangible goods, necessitating tailored life cycle definitions for different cases (Anon n.d.-a). Table 3.2 shows a summary of LCA history.

Event	Year	Note
The (perhaps) *first* LCA-oriented study was presented on energy requirements for the production of chemical intermediates and products	1963	World Energy Conference, Harold Smith
Coca Cola commissions its *first* study comparing beverage containers	1969	Not public
The methodological foundation for environmentally extended input/output analysis is made	1970	Leontief (1970)
Publication of the *first* public and peer-reviewed LCA study "Resource and Environmental Profile Analysis of Nine Beverage Container Alternatives", commissioned by the US EPA	1974	EPA (1974)
First impact assessment method based on critical volumes introduced	1984	BUS (1984)
The *first* widely used commercial LCA software, GaBi, was released in its *first* version	1989	Thinkstep (2016)
SimaPro, another widely used commercial LCA software, was released in its *first* version	1990	PRé (2016)
The term "life cycle assessment" was coined	1990	SETAC (1991)
Emergence of a number of LCI databases managed by different institutions	Early1990s	
First environmental theme-oriented impact assessment methodology, CML92	1992	Heijungs et al. (1992)
SETAC Code of Practice published in effort to harmonise LCA framework, terminology and methodology	1993	SETAC (1993b)
The academic journal fully dedicated to LCA, The International Journal of Life Cycle Assessment, was born	1996	
ISO 14040 standard on LCA principles and framework released	1997	ISO 14040
ISO 14041 standard on goal and scope de*fi*nition released	1998	ISO 14041
Damage-oriented methodology Eco-indicator 99 emerges	1999	Goedkoop and Spriensma(2000)
ISO 14042 standard on life cycle impact assessment released	2000	ISO 14042
ISO 14043 standard on life cycle interpretation released	2000	ISO 14043
UNEP/SETAC Life Cycle Initiative launched	2002	
The LCI database ecoinvent version 1.01 is released	2003	Ecoinvent (2016)
Establishing of a general methodological framework and guideless for LCA through ISO 14040 and ISO 14044	2006	
A framework for Life Cycle Sustainability Analysis was proposed	2008	Klöpffer (2008)
ILCD handbook published	2010	EC (2010)
further EU standardization in International LCA Data (ILCD) System	2012	
PEF and OEF guidelines published	2012-2013	ISO 14046
‚LCA standardization for buildings&construction	2013-2015	LEEDv4 (US) ‚BREEAM (UK), EN15643 (EU)
standardizes process for Produce Category Rules	2017	PCR (1402x)

Table 3-5: summarizes Important elements of the LCA's history, (Hauschild et al., 2018)&LCA class,winter2023, Appendix D, Page 449

3.3.3 Operational Steps to Apply Life Cycle Assessment in Sustainable Design

A standard LCA typically follows these four stages:

Mapping: Identifying and quantifying resource flows and environmental emissions associated with the life cycle.

Classification: Categorizing these emissions based on their impact types (e.g., global warming potential, acidification).

Characterization: Calculating the potential environmental impacts based on scientifically established characterization factors.

Innovation: Analysing the results to identify potential improvements across the product or system's life cycle (Kim and Chae 2016)(Rodrigues 2024)

3.3.4 Application of Life Cycle Assessment

Life Cycle Assessment offers a versatile toolkit that benefits decision-making at multiple stages of product or system development:
Early-Stage Design: In the initial concept phase, LCA allows for the environmental impact assessment of various design choices or materials. This facilitates informed comparisons and trade-offs, ultimately guiding the selection of solutions with optimized sustainability profiles (Quernheim et al. 2023)
Project Optimization: As development progresses, LCA becomes even more valuable. It pinpoints environmental hotspots throughout the life cycle, identifying those areas where targeted changes would yield the most significant sustainability improvements. This data-driven approach ensures that optimization efforts focus on the most impactful aspects.
Environmental Product Declarations (EPDs): The rigorous, quantifiable insights derived from an LCA form the backbone of credible EPDs. EPDs provide transparent and standardized environmental information about a product, empowering stakeholders (consumers, designers, architects, etc.) to make informed choices based on verified sustainability data (Luz et al. 2018).
By understanding the interconnected nature of these uses, it becomes clear how LCA can drive informed decision-making throughout the entire product or system lifecycle, fostering a more environmentally conscious approach from concept to implementation (Pacana et al. 2023).

3.3.4.1 LCA in the Construction Sector: A Holistic Approach to Sustainable Building

Life Cycle Assessment plays a transformative role in the construction industry, enabling the shift towards more sustainable building practices. Here's how it drives this change:
Construction Products: Decoding Environmental Performance EPDs, rooted in LCA methodology, provide standardized and verified environmental impact data for various construction products and materials. This includes crucial metrics such as embodied carbon, water use, and resource depletion potential. By accessing this information, architects, engineers, and procurement specialists can make comparisons and select materials that minimize a building's environmental footprint (Xue et al. 2021).
Building Assessment: Beyond Individual Materials, LCA extends its scope to the assessment of entire buildings. This comprehensive analysis encompasses both:
Embodied Impacts: The cumulative environmental effect of all materials used in the building's construction, along with the impacts associated with the construction processes themselves (Dsilva, Zarmukhambetova, and Locke 2023).
Operational Impacts: The ongoing environmental burden of a building throughout its use phase, primarily driven by energy consumption for heating, cooling, and lighting. This holistic lifecycle perspective allows designers and building owners to optimize overall building sustainability, going beyond individual material choices.
Sustainable Building Certifications: Data-Driven Recognition LCA has become an indispensable tool in achieving credible sustainable building certifications. Schemes like the German Sustainable Building Council (DGNB) often mandate the use of LCAs

to quantify and benchmark a building's environmental performance. These rigorous assessments provide validation for sustainability claims and facilitate comparisons between buildings based on their lifecycle impacts (Di Santo et al. 2023).

3.3.5 Life Cycle assessment stages

While there are variations in specific life cycle models, a common framework for assessing the environmental impact of building construction consists of four primary stages:

Product Stage (A1-A3): This encompasses the sourcing of raw materials, manufacturing of construction products, and their transportation to the construction site (Stantec 2023).

Construction Stage (A4-A5): This includes the on-site construction processes, their associated energy consumption, and the environmental impacts of any construction-related waste.

Use Stage (B1-B7): This stage accounts for the operational energy consumption throughout the building's lifespan, including heating, cooling, and lighting, as well as any maintenance, repair, refurbishment, or replacement that occurs over time.

End-of-Life Stage (C1-C4): This considers the processes of deconstruction or demolition, the transportation of waste, and the waste processing, disposal, or potential benefits from recycling or reuse of materials(Collado-Ruiz 2024).

Benefits and loads beyond the system boundary (D): Module D recognizes that the environmental implications of a product or system can extend beyond these traditional boundaries. It accounts for potential benefits or burdens that might occur due to:

- **Reuse:** If a product or its components are reused at the end of its life, this can displace the need for producing new materials, avoiding associated environmental impacts.
- **Recycling:** Recycling materials often reduces the environmental burden compared to extracting and processing virgin materials.
- **Energy Recovery:** In some cases, waste materials might be incinerated for energy recovery, potentially offsetting the use of fossil fuels

The model of research should be structured around its objectives, considering the diverse sources of embodied carbon and the study's goals. Generally, there are four product life cycle models. The European EN 15978 standard, which is gaining recognition as a common method for defining the system boundary in whole-building Life Cycle Assessment (LCA), illustrates this approach (Li et al. 2014). According to this standard, the system boundary encompasses four main life cycle stages: Product stage, Construction stage, Use stage, and End-of-Life stage. These are further divided into 16 sub-stages (EN BS 2011) as depicted in Figure 3.5 (Masson 2023).

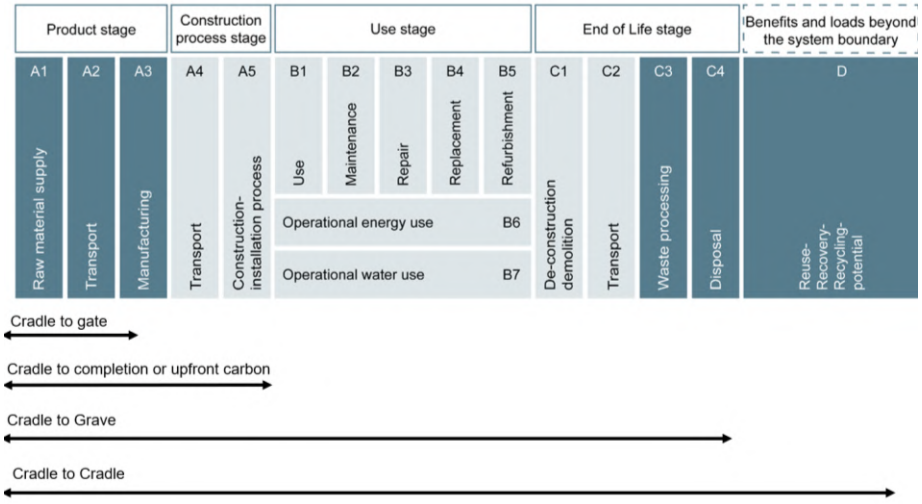


Figure 3-13: Different stages of life cycle assessment.(Reference:www.Oncicllca.com based onEN1580 with edition), Appendix E Page468

Gate-to-gate:

Cradle-to-gate only assesses a product until it leaves the factory gates before it is transported to the consumer. This means cutting out the use and disposal phase. Cradle-to-gate analysis can significantly reduce the complexity of an LCA and thus create insights faster, especially about internal processes. Cradle-to-gate assessments are often used for environmental product declarations (EPD).

Cradle to grave:

analyzing a product's impact along the 5 product lifecycle steps – this is called cradle-to-grave. Cradle being the inception of the product with the sourcing of the raw materials, grave being the disposal of the product. Transportation is mentioned as step 3, but can occur in between all steps.

Cradle to cradle:

Cradle-to-cradle is a concept often referred to within the Circular Economy. It is a variation of cradle-to-grave, exchanging the waste stage with a recycling process that makes it reusable for another product, essentially "closing the loop". This is why it is also referred to as closed-loop recycling. In Regenerative design method modelling and analysis are based on cradle-to-cradle phase.

There are Various certifications for measuring at various phases of the life cycle (Collado-Ruiz 2024) (Castro-Molinare, Korre, and Durucan 2014) (Table 3.3).

Cradle to Gate	Cradle to Grave	Cradle to Cradle
A1 to A3	A1 to C4	**A1 to D**
Product LCA accordingto EN15804:A1	**E.g. LEED**	**E.g. BREEAM, RICS, GLA**

Table 3-8: Different measurement in life cycle stages

3.3.6 Life Cycle assessment Phases

The phases of a Life Cycle Assessment are defined in the ISO standards 14040 and 14044. But as figure 3-3 shows, the different steps depend on each other.

1. **Definition of Goal and Scope:** This phase defines the objectives and the reasons for carrying out the study the scope also includes functions, functional units, system boundaries, allocation procedures, data requirements, and limitations (Rodriguez and Simonen 2017)
2. **Inventory Analysis:** This phase is the stage for data collection of emission and resource use data from life-cycle databases. This is a comprehensive and critical phase since LCA results rely on the quality of LCI (Collinge, et al. 2015)
3. **Impact Assessment:** this phase models the LCI data and translates this into quantifiable environmental impacts. Three substages of the LCIA include the definition of impact categories, classification, and characterization.
4. **Interpretation:** LCI and LCIA results are interpreted and improved to present meaningful information for decision-makers (ISO 2006).

Moreover, the interpretation of the LCA doesn't always have to depend on the actual assessment being finished. Especially when a Life Cycle Assessment becomes more complex, continuously interpreting the results helps optimize the analysis as it goes further down the process (Figure 3.3).

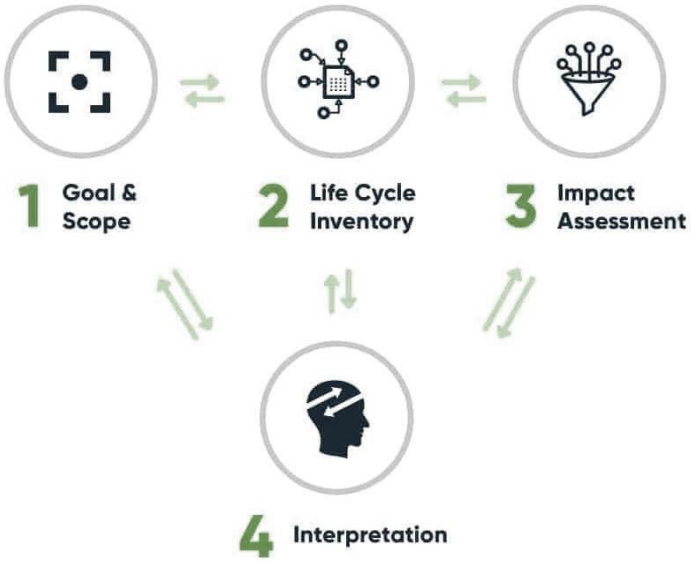


Figure 3-16: dependency of different phases of life cycle assessment (Reference: ustainabilityservices.eurofins.com)

3.3.7 Life cycle Impact Assessment (LCIA)

Life Cycle Impact Assessment (LCIA) is a phase within the Life Cycle Assessment (LCA) process that aims to evaluate and understand the environmental impacts associated with a product or service over its entire lifecycle. This assessment involves both qualitative and quantitative analysis, focusing on the potential environmental consequences of various lifecycle stages, from raw material extraction through production, use, and disposal. LCIA interprets data from the Life Cycle Inventory (LCI), which documents inputs and outputs in the process, to assess their potential environmental impacts. The goal is to identify and quantify these impacts, such as resource depletion, climate change, and ecosystem damage, providing a basis for decision-making and potential improvements in the product's environmental performance (Mu, Xin, and Zhou 2019).

3.3.7.1 Some Data Sources for Energy/Emission Factors:

- Embodied energy or embodied carbon of materials
    - GHG protocol (http://www.ghgprotocol.org/calculation-tools)
- Energy system of states
    - EIA (http://www.eia.gov/state/seds/)
- Electricity from a specific power plant or region
    - EPAe-GRID: (http://www.epa.gov/cleanenergy/energy-resources/egrid/index.html)
    - National Emission Inventory (http://www.epa.gov/ttn/chief/net/2011inventory.html)
- Emissions from various activities
    - EPA compilation AP-42: (http://www.epa.gov/ttnchie1/ap42/)
    - EIA GHG reporting :(http://www.eia.gov/survey/form/eia_1605/coefficients.html)
    - IPCC (http://www.ipcc-nggip.iges.or.jp/EFDB/main.php) [not easy to use]

3.3.7.2 Step of Life Cycle Impact:

Stated the ISO 14040 Impact Assessment is aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system. It categorizes in 4 step, includes, Classification, Characterization, Normalization, valuation (Hauschild and Huijbregts 2015) (Figure3.7).

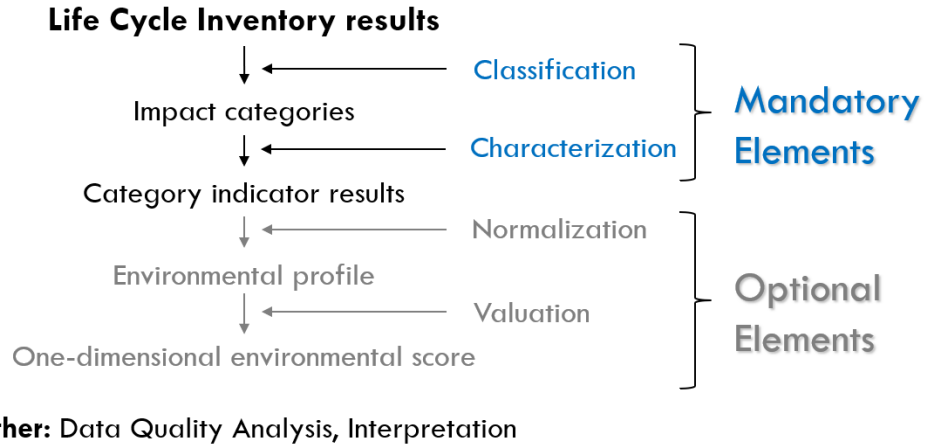


Figure 3-19: Step of Life LCIA,(Hauschild and Huijbregts 2015)

3.3.8 The International Standards as the Constitution of Life Cycle Assessment: The ISO 14040, ISO 14044 Series, and its Offspring

Following the establishment of the SETAC (Society of Environmental Toxicology and Chemistry) code of practice for LCA in 1993, a formal standardization process was

initiated by the International Organization for Standardization (ISO). This process aimed to develop a global standard for LCA, building upon the achievements in scientific consensus achieved in previous years. The necessity for standardization arose from industry demand, as businesses increasingly sought to use LCA for product development and the marketing of environmentally friendly products. However, the absence of a standardized methodology meant that LCA studies of the same product could yield contradictory results, contingent on the methodological choices made.
This initiative culminated in the creation of the ISO 14040 series, which includes four standards that were released over seven years. These standards cover the principles and framework (ISO 14040), goal and scope definition (ISO 14041), life cycle impact assessment (ISO 14042), and life cycle interpretation (ISO 14043). In a 2006 revision, the latter three standards were amalgamated into ISO 14044, which detailed the requirements and guidelines while maintaining the standards' initial requirements.
Moreover, the ISO 14040 series standards focus on the methodology of LCA within the broader ISO 14000 series of Environmental Management standards. This series also includes standards and technical guidance on applying LCA, such as eco-design (ISO 14062, ISO 14006), communication of environmental performance (ISO 14020 series on ecolabels and ISO 14063), and greenhouse gas reporting and reduction (ISO 14064) (ISO 2022).

3.3.9 Life cycle Assessment Inventory Resources

The Life Cycle Inventory (LCI) phase in LCA focuses on the meticulous collection and analysis of data on resource use and environmental emissions throughout a product's or system's life cycle. Various tools support this process:

General Tools: Spreadsheets and statistical software offer flexibility but require a strong understanding of LCA methodology and data organization.
Specialized LCA Software: Programs like openLCA, SimaPro, and GaBi provide a structured framework specifically designed for LCA. They often include built-in databases, impact assessment methods, and visualization features.
Industry-Specific Tools: Certain sectors, like agriculture and food production, have specialized software tailored to streamline LCI calculations based on industry-specific data and processes.

LCI databases compile the results of rigorous studies that quantify the embodied resources, energy use, and emissions associated with thousands of materials, products, and processes. Some key LCI databases widely used by LCA practitioners include:

- **ecoinvent:** A comprehensive, peer-reviewed database focusing on global supply chains and average data.
- **U.S. LCI Database:** Provides U.S.-specific data for various industries and processes.
- **GaBi Databases:** Offers both general and sector-specific datasets.
- **Industry-Specific Databases:** Many sectors maintain specialized databases relevant to their materials and processes (e.g., building materials).

When selecting Life Cycle Inventory (LCI) resources, it is important to consider the following items:

Scope: General databases like ecoinvent provide extensive coverage, while others may focus on specific industries. It's crucial to select a resource that adequately covers the range of materials and processes relevant to your study.
Data Quality: Give preference to databases with transparent methodologies, well-established peer-review processes, and comprehensive documentation. High-quality data are essential for the accuracy and reliability of LCA results.
Geographic Relevance: Opt for databases that are geographically pertinent to your project's location, or the origin of the materials being analyzed. This ensures the environmental impacts are accurately represented based on local or regional conditions.
Compatibility: Verify that the LCI data format is compatible with your LCA software. Compatibility is key to seamless integration of data into your life cycle assessment studies.
LCI resources are instrumental in enabling stakeholders to make informed, data-driven decisions that enhance sustainability. They help in identifying opportunities to minimize environmental impacts throughout the life cycle of products and systems.

3.3.10 Life cycle Assessment Tools and software

Life Cycle Assessment (LCA) employs a diverse range of tools and software. Researchers can choose from various options based on the objectives and scope of their study and the phases involved. A comprehensive understanding of all available tools is essential, as it allows researchers to select the most appropriate ones for their specific research needs. The following sections will introduce and compare the software commonly used in Life Cycle Assessment, providing insights into their features, capabilities, and suitability for different types of LCA studies.

3.3.10.1 Ecochain Mobius

Ecochain Mobius is renowned for being one of the most user-friendly Product Footprint and Life Cycle Assessment (LCA) tools on the market. It features an intuitive interface and comprehensive guidance within the tool, enabling users to quickly learn how to assess and enhance the environmental footprint of their products. Ecochain Mobius provides access to some of the largest environmental impact databases, including EcoInvent, the Environmental Footprint (EF), and the Dutch Nationale Milieudatabase (NMD), at no additional cost. These databases offer detailed environmental information on a wide range of materials, ingredients, and components.
Ideal For: Ecochain Mobius is particularly well-suited for users who aim to integrate sustainable product design within a company. The tool facilitates the easy testing and analysis of the impact of alternative materials in product designs, allowing for iterative improvements through an accessible scenario functionality. It enables users to compare different product designs and benchmark their Product Footprint against industry averages.
Users: Mobius is used by professionals in roles such as R&D, Product Design, Product Management, Engineering, Quality, Health, Safety, Environment (QHSE), and Sustainability Management. Its intuitive design makes it accessible for beginners in environmental impact measurement, while still offering the depth and functionality that intermediate and expert users appreciate for creating and collaborating on their LCA projects.

3.3.10.2 Ecochain Helix:

Ecochain Helix is designed to assist manufacturing companies in measuring and improving the environmental footprint of their complete product portfolios and large-scale production facilities. It facilitates the creation of Life Cycle Assessments (LCAs) in bulk, utilizing a top-down approach known as Activity-based Footprinting.
Helix offers high-level steering information for companies and features dashboards that display environmental performance at the company, process, and product levels. Furthermore, it enables the generation of Product Footprints, LCA reports, and Environmental Profiles (LCA results) for the entire product portfolio simultaneously.
Ideal for: Ecochain Helix is utilized across various industries, including construction, packaging, food, agriculture, and chemicals. While the tool itself is not overly complex, the data collection process and the entry of all input data can be more extensive than creating an LCA for a single product. As such, Ecochain Helix is well-suited for users who are experienced LCA practitioners.
Users: The tool is primarily used by Sustainability Managers, Product or Facility Managers, and LCA consultants, who rely on Helix to generate comprehensive environmental insights.

3.3.10.3 GaBi:

GaBi, established in the mid-1990s, is a well-recognized Life Cycle Assessment (LCA) tool extensively used across various industries, particularly in its home market of Germany. Similar to SimaPro, GaBi offers a comprehensive technical solution with a wide range of potential add-ons for sustainable product development. It is frequently utilized by LCA experts and sustainability consultants. GaBi operates with its proprietary Life Cycle Inventory (LCI) database, enabling the execution of LCAs according to different standards. Beyond LCAs, GaBi also facilitates Life Cycle Costing and Life Cycle Reporting.
Ideal for: GaBi is often deemed most suitable for LCA experts. It is the tool of choice for those looking to conduct complex and in-depth analyses of a product's footprint. GaBi, along with Sphera, provides all the necessary tools for such detailed assessments.
Users: Primarily, LCA experts and sustainability consultants use GaBi to leverage its robust capabilities for thorough environmental analysis and sustainable product development.

3.3.10.4 OneClickLCA:

One Click LCA is uniquely tailored for the construction sector, making it the only application on our list dedicated to this industry. It offers numerous functionalities specifically designed for construction needs, including various modeling and reporting features that are well-suited for companies producing building materials or construction products. The tool also allows for the analysis of environmental impacts associated with construction projects and buildings. Originating from Finland, One

Click LCA effectively supports certifications like LEED (USA), DGNB (Germany), and BREEAM (UK).

Ideal for: One Click LCA is best suited for professionals in the construction industry who are experienced in Life Cycle Assessment and require a tool that offers comprehensive solutions for measuring and reporting environmental impacts.
Users: Primarily used by LCA practitioners in the construction field, One Click LCA helps them to efficiently assess and document the environmental performance of their projects and products.

3.3.10.5 Open LCA:

OpenLCA is an open-source software solution that can be utilized at no cost, offering several advanced functionalities suitable for users with a technical background. The software allows for the customization of Life Cycle Inventory (LCI) datasets, enabling adjustments to reflect specific production processes and inputs of a product. Furthermore, OpenLCA boasts a range of analytical features for assessing the environmental impact and performance of products.
With OpenLCA, users can conduct an in-depth investigation of environmental datasets, facilitating advanced supply chain analysis. As LCA tools depend on LCI databases to measure impact, OpenLCA provides access to a wide array of databases. However, it is important to note that many of these databases are not free of charge.
Ideal for: OpenLCA is particularly appealing for those new to the LCA field without a significant budget, offering a robust platform for in-depth environmental analysis. While it serves as an accessible tool for beginners, it is also well-suited for more advanced practitioners, LCA experts, and sustainability consultants due to its comprehensive features.
Users: OpenLCA is a systems modeling tool extensively used by LCA experts and sustainability consultants to quantify the total resource inputs and environmental burdens associated with a product, making it a valuable tool for those engaged in detailed and complex environmental assessments.

3.3.10.6 SimaPro:

SimaPro, established 30 years ago, has become one of the most recognized LCA software tools in the market. It offers both desktop and cloud-based solutions, although the latter may not include all features. Known for its technical complexity, SimaPro provides a wide range of optional add-ons, enhancing its versatility. The software allows users to conduct detailed LCA calculations for products and production processes.
Ideal for: SimaPro is particularly suited for use in academic settings and by experienced LCA consultants. As noted on their website, it is designed for seasoned LCA experts, facilitating the modeling and analysis of complex life cycles in a systematic manner.
Users: SimaPro enables users to assess the environmental impact of products and services throughout all life cycle stages, making it a preferred tool for professionals who require a comprehensive and detailed analysis capability (Ecochain 2024).
The results are summarized as an overview in Table 3.4.

Table 3-11: Comparison of life cycle assessment tools,(Reference: ecochain.com), Appendix D, Page 450)

	Eco chain Mobius	Ecochain Helix	GaBi	Oneclicklca	openLCA	SimaPro
Ease of use	Easy	Moderate	Moderate to difficult	Moderate to difficult	Moderate to difficult	Moderate to difficult
Free Trial	Yes, 14-day free trial	No, but demo is available	Yes, 30-day free trial	Yes, 14-day free trial	N.A. Free software	No, but you can download a demo version
Cloud-based Application	Yes	Yes	No, download only	Yes	No, download only	No, download only
URL	ecochain.com/mobius	ecochain.com/helix	www.gabi-software.com	www.oneclicklca.com/	www.openlca.org/	www.simapro.com

Following the detailed examination of various Life Cycle Assessment (LCA) tools and software, the tools used in the construction sector have been classified in Table 3.5.
The table compares various tools and databases used for Life Cycle Assessment (LCA) in terms of their functionalities and features. GaBi, BEES, USLCI, Athena IE for Buildings/Eco-Calculator, NIST BIRDS, One-click LCA, Tally, Ecoinvent, OpenLCA, and the Kaleidoscope Tool are included. Each tool's inclusion of Life Cycle Inventory (LCI) databases, its specialization in LCA tools for building materials and assemblies, and its capability as a whole-building LCA tool are assessed. Tools like GaBi, BEES, Athena IE for Buildings/Eco-Calculator, and Ecoinvent include LCI databases. Specifically, Athena IE and Tally stand out by offering both LCA tools for building materials and whole-building LCA tools. OpenLCA is versatile, providing all three functionalities: an LCI database, tools for building materials, and whole-building LCA tools. This comprehensive comparison highlights OpenLCA's flexibility and extensive support, making it a valuable tool for detailed environmental impact assessments. Table 3.5 presents a comparison of tools and Databases.

Tools & Database		Includes LCI database	LCA tools *specifically* for building materials/assemblies	Whole-building LCA tools
GaBi	GaBi	*		
BEES	BEES	*	*	
FEDERAL LCA COMMONS	USLCI	*		
Athena Sustainable Material Institute	Athena IE for Buildings/ Eco-Calculator	*	*	*
NIST National Institute of Standards and Technology U.S. Department of Commerce	NIST BIRDS			*
One Click LCA	One-click LCA			*
tally	Tally (http://choosetally.com/tutorials/)			*
ecoinvent	Ecoinvnet	*		
openLca	Open ICA	*	*	*
	Kaleidoscope Tool (Online access)		*	

Table 3-14: Tools and data base for construction sector, Appendix D, Page 450

3.3.11 Gaining Expertise in Life Cycle Assessment in Boston: Emphasizing OpenLCA

During my studies in Boston, particularly at Northeastern University, I learned various software tools for life cycle assessment (LCA), which offered unique features and capabilities for conducting comprehensive sustainability assessments. Additionally, I explored several online tools that provided accessible platforms for LCA analysis. However, we ultimately focused on using OpenLCA due to its versatility, open-source nature, and extensive database support. OpenLCA's flexibility in modeling complex systems and its integration with various databases such as ecoinvent and Agribalyse made it an ideal choice for our detailed environmental impact assessments. This tool allowed us to customize our analyses and ensure accurate and transparent results, aligning perfectly with our research objectives and methodology. My experience in Boston, surrounded by leading experts and innovative research, significantly enhanced my proficiency in LCA, directly benefiting the methodological framework of my thesis.

3.4 Environmental Product Declaration

EPD (Environmental Product Declaration) is a concise document that describes the environmental impact of a product or service. The abbreviation EPD is derived from the English term Environmental Product Declaration and is usually translated into German as Umwelt-Product declaration. An EPD is a document in which the environmentally relevant properties of a product are outlined in the form of neutral and objective data. This data covers as many impacts as possible that the product can have on its environment, whereby in an ideal situation, the entire life cycle of the product is taken into consideration.

In the area of construction, EPDs represent an essential basis for experts such as architects and planners when it comes to the comprehensive planning and evaluation of buildings. However, EPDs are not usually suitable for direct comparisons of products as the degree of environmental friendliness, conservation of resources, or sustainability displayed by a construction product is largely dependent on the (building) context in which it is used. An EPD is a transparent, verified report of the environmental impacts of product manufacturing. Also known as Type III Environmental Declarations, EPDs are product labels developed by industry in accordance with the International Organization for Standardization (ISO) Standard 14025 (ISO 2006). They are developed using life-cycle assessment (LCA) procedures and following the industry consensus methodology described in the governing Product Category Rules (PCR) document. As specified in ISO 14025, EPDs undergo third-party verification before being published. (Fhwa n.d.)

An Environmental Product Declaration (EPD) is essentially an externally verified and standardized description of the environmental profile of any product or material over its lifetime. If you are a construction engineer or an architect, you can easily compare the EPD data of the materials you are about to use and choose the most sustainable option. If you are a manufacturer, by certifying your product with this methodology you are making a positive value statement on the issues of climate change, carbon impact, and environmental footprint. Having an EPD for a product does not necessarily mean that the product is environmentally better than others, but it is a way to obtain transparent information on the environmental impact of the product during its whole lifetime.

EPDs are based on Life-cycle assessment calculations according to ISO 14040, ISO 14044 and usually EN 15804 standards in European countries. An EPD is created and verified in accordance with the International Standard ISO 14025, developed by the International Organization for Standardization (ISO) (Steen 2006). In Europe, the European Committee for Standardization has published EN 15804, common Product Category Rules (PCR) for EPD development in the construction sector. EPDs help to achieve EPD and LCA credits in the following certification schemes: LEED, BREEAM, DGNB, HQE, and others. They are usually valid for five years (Zacharia 2024)(environdec.com 2024)(ecochain 2024).

3.4.1 Advancing Knowledge of Environmental Product Declarations in Through Research Experience in Boston

During my studies in Boston, I undertook a project focused on Environmental Product Declarations (EPDs). This project allowed me to understand the significance of EPDs in sustainable design and how selecting products based on their EPDs can contribute to achieving LEED standards. EPDs provide detailed information about the environmental impact of products throughout their lifecycle, helping designers make informed choices that align with sustainability goals. By improving my knowledge of EPDs, I realized the importance of choosing materials with verified EPDs for my prototype. This approach

not only ensured compliance with LEED standards but also provided a robust basis for modeling and analyzing the environmental performance of the materials used in my research. Consequently, my methodology incorporated the selection of EPD-verified materials, which played a crucial role in addressing my research questions and advancing the field of sustainable architectural design.

3.5 Product Category Rules (PCRs)

Product Category Rules (PCRs) are standardized guidelines used in the development of Environmental Product Declarations (EPDs). They dictate the specific criteria and procedures that must be followed during the life cycle assessment (LCA) of products, ensuring consistency and comparability between EPDs of similar products. PCRs outline:
Materials and Processes: They specify which materials and processes should be included in the analysis, focusing on those with significant environmental impacts.
Declared Unit: PCRs define the declared unit for the product, facilitating a clear and consistent basis for comparison.
In the context of the European Standard, general PCRs for Type III environmental declarations are provided for wood and wood-based products used in construction. These complement the core rules established in EN 15804 and are intended for use alongside this standard.

The core PCR aims to:

- Define the environmental parameters to be declared and the method of their aggregation and reporting.
- Determine the life cycle stages and processes to be included in the EPD.
- Establish rules for developing scenarios.
- Set guidelines for the calculation of the Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA), including data quality specifications.
- Dictate the reporting of environmental and health information not covered by the LCA.
- Establish conditions for the comparison of construction products based on EPD information.

For wood and wood-based products, the European Standard further specifies:

- System boundaries for the LCA.
- Modelling and assessment rules for material-specific characteristics, including carbon storage and energy content.
- Allocation procedures for multi-output processes and for reuse, recycling, and energy recovery.
- Calculation rules for the LCI and LCIA, including assessments of carbon and energy content.
- Guidelines for determining the Reference Service Life (RSL).

This standard supports both "cradle to gate" and "cradle to grave" assessments, requiring clear statements of intent within the system boundary descriptions. By standardizing the assessment process, PCRs ensure that the environmental impacts of products are evaluated in a transparent, comparable, and comprehensive manner, aiding stakeholders in making informed decisions regarding the sustainability of products (environdec 2023) (Figure 3.8).

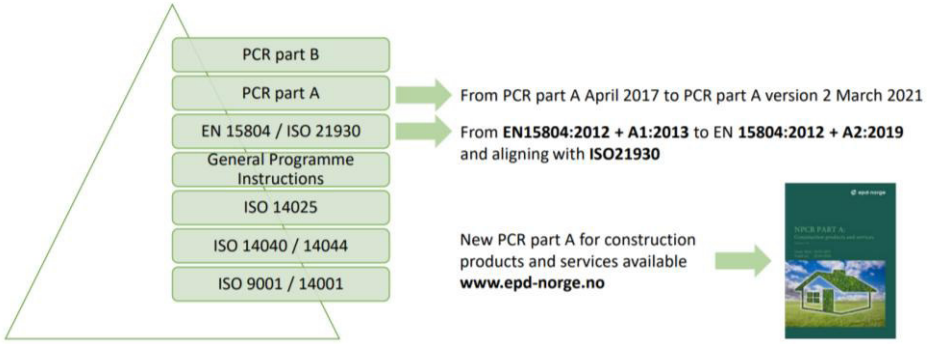


Figure 3-22: PCR for construction Product, Reference: https://www.epd-norge.no/,

3.5.1 EN 16485:

EN 16485 provides general Product Category Rules (PCR) for Type III environmental declarations for wood and wood-based products for use in construction and related construction and in-service processes. This European Standard complements the core rules for the product category of construction products as defined in EN 15804 and is intended to be used in conjunction with EN 15804. The core PCR: - define the parameters to be declared and the way in which they are collated and reported; - describe which stages of a product's life cycle are considered in the EPD and which processes are to be included in the life cycle stages; - define rules for the development of scenarios; - including the rules for calculating the Life Cycle Inventory and the Life Cycle Impact Assessment underlying the EPD, including the specification of the data quality to be applied; - including the rules for reporting predetermined, environmental and health information, that is not covered by LCA for a product, construction process and construction service where necessary; - define the conditions under which construction products can be compared based on the information provided by EPD. For the EPD of construction services, the same rules and requirements apply as for the EPD of construction products. Additionally to the common parts of EN 15804, this European Standard for wood and wood-based products: - defines the system boundaries; - defines the rules for modeling and assessment of material-specific characteristics such as carbon storage and energy content of wood; - defines allocation procedures for multi-output processes along the wood chain; - defines allocation procedures for reuse, recycling and energy recovery; - includes the rules for calculating the Life Cycle Inventory and the Life Cycle Impact Assessment underlying the EPD, including the assessment of carbon and energy content of wood; - provides guidance/specific rules for the determination of the Reference Service Life (RSL). This European Standard is intended to be used for cradle-to-gate or cradle-to-grave assessment, provided the intention is properly stated in the system boundary description (Achenbach et al. 2016)

3.5.2 EN 15804:

A PCR (Product Category Rules) is normally developed as a supplement to EN 15804 and contains an additional set of rules for specific product categories.
The purpose of this document is to define clear guidelines when performing a life cycle assessment (LCA), to ensure that the same LCA methods are being used for any product group, and to support the modularity principal so that each EPD can be used as an information source for construction works. This standard harmonizes the structure

for EPDs in the construction sector, making the information transparent and comparable (ibu-epd.com 2017)
As stated in the above explanation diagram 3.4 shows the EPD production Process from the Iso standard. Diagram 3.4 shows the EPD production process from standards.

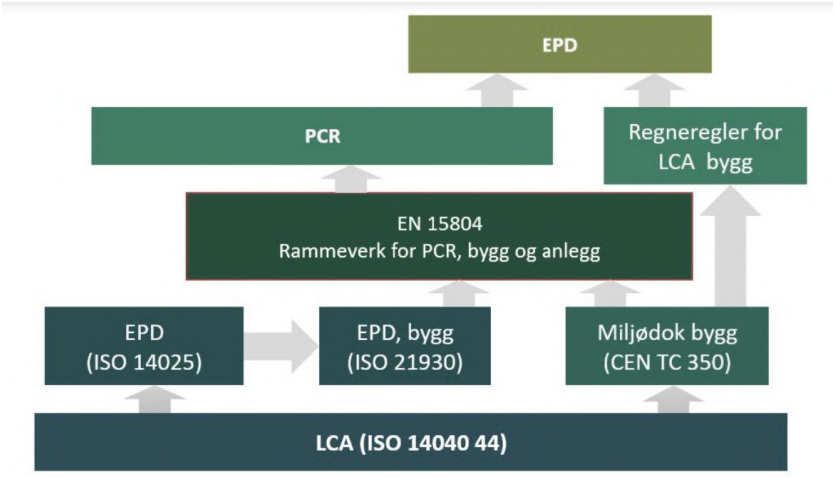


Diagram 3-11: EPD production process from standards(Reference: Onecliclca.com)

3.5.2.1 Revision of EN 15804

The NS-EN 15804:2012 + A2:2019 standard, adopted in Norway in 2019, significantly updates guidelines for creating Environmental Product Declarations (EPDs) in the construction sector. This revision aligns with advancements in Life Cycle Assessment (LCA) methodology and the European Union's Product Environmental Footprint (PEF) initiative.

- **Key Changes Introduced by A2:2019:**
  - Mandatory Lifecycle Reporting: Modules C (end-of-life) and D (benefits beyond system boundary) are now generally required. This mandates a more comprehensive analysis of a product's environmental impact throughout and beyond its lifespan.
  - Biogenic Carbon Accounting: EPDs must now disclose the biogenic carbon content within the product and its packaging.
  - Expanded Impact Indicators: A2 aligns with PEF for standardized impact reporting and includes additional indicators addressing a wider range of environmental concerns (e.g., eutrophication).
- **Implications of A2:2019:**
  - EPD Comparability: Results of EPDs created under A2 will generally not be directly comparable to those based on the older A1 version due to differences in methodology.
  - Enhanced Transparency: The inclusion of biogenic carbon, end-of-life stages, and additional indicators provides a more detailed picture of a construction product's environmental footprint.
  - Data Quality: A2 emphasizes comprehensive data quality assessment to ensure the reliability of LCA results (ibu-epd.com 2017).

3.5.3 Use of Standards in Analysis

In this thesis, the selection and analysis of materials across different cladding systems were meticulously guided by the European standards EN 15804 and ISO 14025. These standards were instrumental in defining the framework for assessing the life cycle environmental impacts of construction materials, particularly focusing on Global Warming Potential (GWP). Adhering to these standards ensured that the environmental assessments were comprehensive, transparent, and consistent with international sustainability practices. This methodology allowed for reliable comparisons between different cladding options and reinforced the scientific validity of the material choices based on their environmental performance metrics.
Furthermore, the application of these standards was pivotal in deriving data-driven insights that informed the sustainability recommendations provided in this thesis. By quantifying the environmental impact through standardized indicators such as GWP, the research supports well-informed architectural decisions aimed at minimizing ecological footprints and advancing the pursuit of climate-resilient building designs.

3.6 TRACI: Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI):

TRACI is an environmental impact assessment tool. It provides characterization factors for Life Cycle Impact Assessment (LCIA), industrial ecology, and sustainability metrics. Characterization factors quantify the potential impacts that inputs and releases have on specific impact categories in common equivalence units. Impact categories include:

- ozone depletion,
- climate change,
- acidification,
- eutrophication,
- smog formation,
- human health impacts, and
- ecotoxicity.
- Fossil fuel depletion

Users of TRACI include LCIA practitioners and researchers. TRACI can be applied to processes, products, facilities, companies, and communities. TRACI can be updated as advances in LCIA research occur.(Bare 2011).

3.7 Green Building Certification Program

A sort of building certification system called a rating system assigns points or trophies based on how well a building performs in relation to certain environmental goals and guidelines. It's common to use the terms rating systems and certification systems interchangeably. Green building rating and certification systems require an integrated design process to create projects that are environmentally responsible and resource-efficient throughout a building's life cycle: from siting to design, construction, operation, maintenance, renovation, and demolition (WBG,2023). In 1998, was piloted

LEED—shorthand for Leadership in Energy and Environmental Design, a rating system for environmentally sound buildings—and the movement went mainstream. (LEED has four levels of certification that step up in rigor: Certified, Silver, Gold, and Platinum.) LEED standards have essentially been written into building codes across the country to ensure that the next generation of homes, offices, warehouses, schools, and hospitals are more resource-conscious than the last. LEED certification is expected for today's high-end office buildings and corporate headquarters. But it is available for virtually any type of construction, including renovations, and even entire neighborhoods and cities. Globally, several green rating systems have been developed to assess the sustainability of construction projects. Their classifications and standards have undergone continuous revisions to reflect the sustainable building development trend (Ebert, Eßig, and Hauser 2011).

Dat Tien Doan et al in 2017 with a research titled "A CRITICAL COMPARISON OF GREEN BUILDING RATING SYSTEMS" compared different contemporary different rating systems. on this article, Specifically, LEED (Leadership in Energy and Environmental Design), BREEAM (Building Research Establishment Assessment Method), CASBEE (Comprehensive Assessment System for Building Environmental Efficiency), and Green Star NZ were analyzed. The results indicate that BREEAM, LEED, and CASBEE have been utilized since late the 2000s while Green Star NZ is still in its earlier stages. 70% of the research papers focusing on BREEAM, LEED, and CASBEE are developed geographically in the USA, Canada, the UK, China, and Australia. Although these four rating systems were initiated in different contexts with different standards, Indoor Environment Quality, Energy, and Material are core common categories for all. Currently, BREEAM has been the only tool which could assess all four sustainable factors (Doan et al. 2019). those standards mainly focus on energy and carbon efficiency and lack the holistic approach of third party certification systems. the accelerating evolution of sustainable building rating systems is evident to importance of an evaluation system to control environmental impact of different construction. Figure 3-9 shows how sustainable building rating systems, construction standards, and building product/materials labeling are rapidly evolving(Leiringer 2020).

Numerous whole building standards and certification systems incorporate life cycle assessment as a criterion for evaluating building sustainability. Each possesses a distinct objective, whether explicit or implicit, ranging from the reduction of greenhouse gas emissions to the enhancement of indoor environmental quality. Table 3.6 presents a summary of green building certifications.

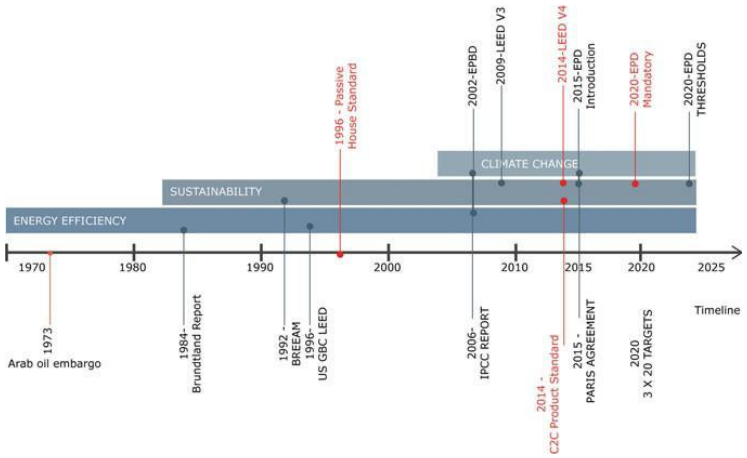


Figure 3-25: Evolution of key influential building rating systems, building standards

building Rating or Certification System	Single- or Multi-Attribute	Type of Standard or Certification	Managing Organization	Issues / Areas of Focus
Building Research Establishment Environmental Assessment Method (BREEAM)	Multi-Attribute	Green building rating and certification system through on-site independent third-party verification for: • New Construction • In-Use • Refurbishment & Fit Out • Communities Infrastructure	BRE Global	Performance in: • Energy • Health & Well-being • Transport • Water • Materials • Waste • Land Use & Ecology • Management • Pollution No prerequisites for In-Use
Leadership in Energy and Environmental Design (LEED)	Multi-Attribute	Green building rating and certification system through independent third-party verification for: • New Construction (NC) • Existing Buildings, Operations & Maintenance (EB O&M) • Commercial Interiors (CI) • Core & Shell (CS) • Schools (SCH) • Retail • Healthcare (HC) • Residential • Cities and Communities	U.S. Green Building Council	Performance in: • Sustainable Sites • Water Efficiency • Integrative Process • Location & Transporation • Energy & Atmosphere • Materials & Resources • Indoor Environmental Quality • Innovation • Regional Priority
Green Globes	Multi-Attribute	Green building guidance and assessment program for: • Existing buildings • New construction	Green Building Initiative in the U.S. BOMA Canada	Environmental assessment areas to earn credits in: • Energy • Indoor Environment • Site • Water Efficiency • Materials

				• Project Management No prerequisites
Living Building Challenge	Multi-Attribute	Performance-based standard, and certification program for: • Landscape and infrastructure projects • Partial renovations and complete building renewals • New building construction • Neighborhood, campus and community design	International Living Future Institute	Performance areas include: • Place • Water • Energy • Materials • Health & Happiness • Equity • Beauty All areas are requirements.
Passive House Institute US	Multi-Attribute	Performance based passive building standard: • Third-party RESNET approved quality assurance/quality control • Earns U.S. DOE Zero Energy Ready Home status • Includes HERS rating	Passive House Institute US	Any type of building. New focus areas include: • air tightness requirements • source energy limit • space conditioning criteria • net zero energy

SITES	Multi-Attribute	Third-party verified rating system for development projects located on sites with or without buildings including: • Open spaces • Streetscapes and plazas • Commercial • Residential • Educational/ Institutional	Administered by GBCI	Performance criteria in the areas of: • Site Context • Water • Soil & Vegetation • Human Health & Well-being • Materials Selection, and more
WELL Building Standard	Multi-Attribute	Performance based standard and certification program for: • New and Existing Buildings • New and Existing Interiors • Core and Shell Retail • Retail • Education Facilities • Restaurant • Commercial Kitchen • Multifamily Residential	Administered by the International WELL Building Institute™ (IWBI)	Measures attributes of buildings that impact occupant health by looking at ten factors: Air, Water, Nourishment, Light, Movement, Thermal Comfort, Sound, Materials, Mind, Community, and Innovation.
Fitwel	Multi-Attribute	• New Construction • Existing Buildings	Center for Active Design	Fitwel's seven health impact categories are: Impacts Surrounding Community Health, Reduces Morbidity and Absenteeism, Supports Social Equity for Vulnerable Populations, Instills Feelings of Well-Being, Enhances Access to Healthy Foods, Promotes Occupant Safety, and Increases Physical Activity
International Programs				

BCA Green Mark Scheme (Singapore)	Multi-Attribute	Benchmarking scheme that aims to achieve a sustainable built environment by incorporating best practices in environmental design and construction, and the adoption of green building technologies.	Building and Construction Authority (BCA)	Rates buildings according to five key criteria: • Energy efficiency • Water efficiency • Environmental protection • Indoor environmental quality, and • Other green and innovative features that contribute to better building performance.
Beam (Hong Kong)	Multi-Attribute	Comprehensive standard and supporting process covering all building types, including mixed use complexes, both new and existing to assess, improve, certify, and label the environmental performance of buildings	Business Environment Council	Performance and assessment in: • Site aspects • Material aspects • Water use • Energy use • Indoor environmental quality • Innovations and additions
CASBEE (Japan)	Multi-Attribute	Building assessment tools for • Pre-design • New Construction • Existing Building and • Renovation	JSBC (Japan Sustainable Building Consortium) and its affiliated sub-committees	Assessment areas include: • Energy efficiency • Resource efficiency • Local environment, and • Indoor environment
EDGE	Multi-Attribute	A universal standard and a certification system for residential and commercial structures.	International Finance Corporation (IFC), a member of the World Bank Group	Assessment areas include: • Energy • Water • Materials

Green Star SA (South Africa)	Multi-Attribute	Green building rating system for: • Office • Retail • Multi-unit residential	Green Building Council of South Africa administers program Independent assessors to assess and score projects	Categories assessed in: • Management • Indoor Environmental Quality • Energy • Transport • Water • Materials • Land Use & Ecology • Emissions • Innovation
Pearl Rating System for Estidama (UAE)	Multi-Attribute	Green building rating system for: • Community • Buildings • Villas • Temporary Villas and Buildings	Abu Dhabi Urban Planning Council	Assessment of performance in: • Integrated Development Process • Natural Systems • Livable Communities • Precious Water • Resourceful Energy • Stewarding Materials • Innovating Practice

Table 3-17: Summary of green building certification, (Reference: www.wbdg.org), Appendix D Page 451

As explained, numerous green building certifications exist, and some countries apply specific certificates to evaluate green buildings. Among these certifications, Table 3.7 provides a summary of the most renowned international green building certifications.

Certification	Supported
BREEAM International	BREEAM Int'l NC 2016, BREEAM Int'l RFO 2015, BREEAM Int'l NC 2013, Commercial EU 2009, Int'l Bespoke 2010
LEED	LEED v4.1, v4, v3 (both BD+C & ID+C credits)
DGNB	DGNB Int'l, DE, DK
Level(s)	Most macro-objectives
Zero Carbon Certification & Living Building Challenge	Can be done in most carbon tools.

Table 3-20:the most renowned international green building , certifications, (Reference: Onecliklca.com), Appendix D, page 454

Understanding sustainable design involves recognizing its focus on minimizing negative environmental impacts while improving the quality of life for building occupants. It encompasses strategic material choices, energy-efficient systems, and practices that promote water conservation and waste reduction. Certifications like LEED (Leadership in Energy and Environmental Design) provide benchmarks for building sustainability, ensuring that structures meet stringent energy and

environmental criteria. Green buildings have been shown to cut operating costs by 8–9%, increase property values by up to 7.5%, offer an enhanced return on investment of up to 6.6%, and even improve occupancy and rental rates (Macaskill and Research Online 2021)(Construction Industry Institud 2008)
The benefits of sustainable design extend beyond finances, positively impacting occupant health and productivity. Improved indoor air quality, increased natural light, and the use of healthier materials all contribute to a better environment for those who live and work in these spaces. LEED-certified buildings provide concrete examples of these benefits, showcasing impressive reductions in energy, carbon, water, and waste – often ranging from 30 to 97%.
Despite the clear advantages, challenges such as upfront costs and regulatory hurdles can sometimes impede the adoption of sustainable design. Overcoming these obstacles requires strategic planning and innovative solutions.

3.7.1 Enhancing Knowledge of Building Rating Systems Through Boston-based Research Experience

During my time in Boston, I took the course "Sustainable Design and Technologies in Construction" under the guidance of Professor David Fannon. This course profoundly impacted my understanding of sustainability in the built environment. I learned about the various aspects of sustainability, including energy efficiency, water conservation, and material selection, and how these are measured to meet LEED standards. The course introduced me to different building rating certifications such as LEED, BREEAM, and WELL, providing a comprehensive overview of each system's criteria and evaluation methods. This experience in Boston enriched my knowledge and informed my methodological approach to my thesis. The in-depth study of building rating systems allowed me to incorporate standardized sustainability metrics into my research, ensuring that my proposed designs not only meet but exceed industry standards for environmental performance. This holistic understanding of sustainability and building certifications has been instrumental in shaping the rigorous, evidence-based methodology that underpins my thesis.

3.8 Rhino Software

Rhino 3D, developed by Robert McNeel & Associates, is a comprehensive software tool for 3D modeling and graphics. It excels in creating, editing, analysing, and translating NURBS curves, surfaces, and solids, subdivision geometry (SubD), point clouds, and more. Its versatility makes it popular in industries like architecture, industrial design, product design, and multimedia. Rhino is known for its mathematical precision, allowing users to craft complex and detailed three-dimensional models with high accuracy (rhino3d.com 2024). Rhino started as a beta version released in April 1994. The latest version available is Rhino 8, which has been launched for both Windows and Mac(McNeel Wiki 2023) (Figure 3.10).

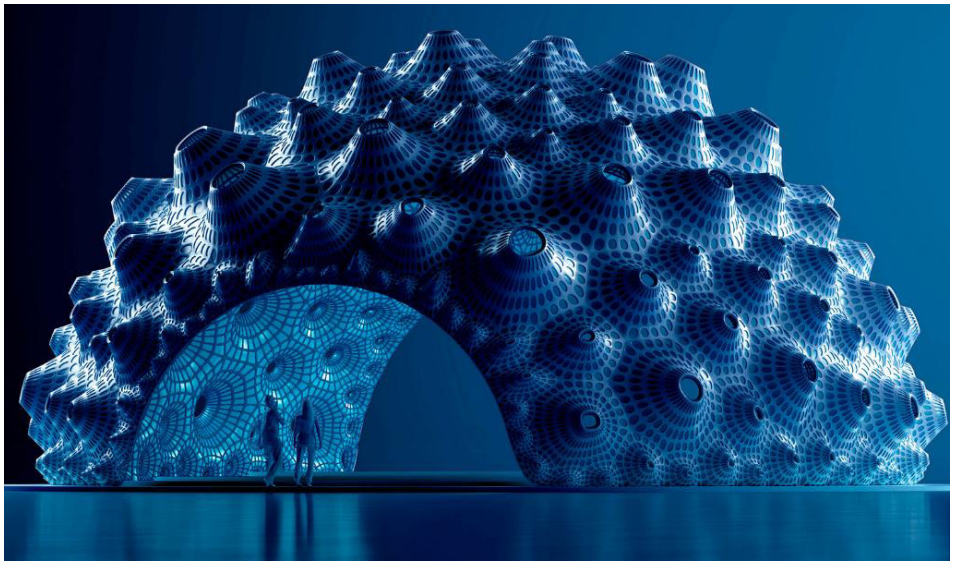


Figure 3-28: Computational Thinking – Studio Ignacio Revenga – PAACADEMY, (Reference: Parametric-Architecture.com)

A.1.1 Rhino Plugins

One notable plugin is Grasshopper, renowned for its power in algorithmic design, enabling users to create complex models through visual programming. Honeybee and Ladybug are plugins integral to architects and designers, providing advanced simulation tools for environmental analysis, energy modeling, and sustainable design, facilitating informed decision-making in the early stages of design. OneClick LCA is another critical plugin, specializing in life cycle assessment, helping users evaluate the environmental impacts of their designs efficiently, supporting sustainable and green building initiatives. These plugins collectively enhance Rhino's utility, making it a comprehensive toolkit for professionals in architecture, engineering, and design, promoting innovation and sustainability in their projects.

3.8.1.1 Grasshopper

Grasshopper is a visual programming language and environment that runs within the Rhino3D software. It provides architects and designers the capability to explore parametric and algorithmic designs without needing to write code. Users can create complex models by defining a sequence of operations, known as a script or definition, which can be adjusted to explore various design outcomes dynamically (Figure 3-11). In fact Grasshopper is a graphical algorithm editor included with Rhino (Tait 2023).

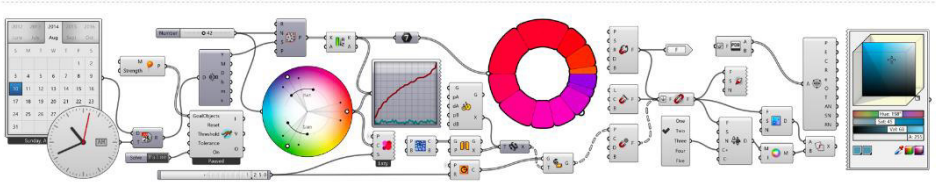


Figure 3-31: Grasshopper , a plugin for Rhino, (Reference: rhino3d.com)

Unlike RhinoScript, Rhino.Python, or other programming languages, Grasshopper requires no knowledge of programming or scripting but still allows developers and designers to develop form-generation algorithms without writing code (Dogan 2023).

The capabilities of Grasshopper in Rhino include the generation of complex geometric forms through parametric algorithms, allowing for a high degree of customization and control over the design process. This makes it particularly useful for tasks that require repetitive calculations, or the generation of forms based on rule-based relationships, such as environmental analyses, structural optimization, and generative art (Schramme 2024).
Grasshopper also supports a wide range of plugins that extend its functionality further. These plugins can introduce new types of geometry manipulation, connect to other software and databases, or add specialized tools for industries like architecture, engineering, and construction (AEC). For example, plugins can allow for the integration of Rhino models with other analytical tools, enhancing capabilities in simulations, data analysis, and material optimization.

3.8.1.2 Ladybug

The Ladybug plugin for Rhino, specifically integrated with Grasshopper, is a powerful tool designed for environmental analysis. It enables architects, designers, and engineers to conduct detailed simulations and analyses of weather and climate data directly within the Rhino 3D environment. Ladybug allows users to import and visualize weather data, and create sun path diagrams, wind roses, psychrometric charts, and more, facilitating the evaluation of building performance and outdoor conditions over time (Figure 3.12).

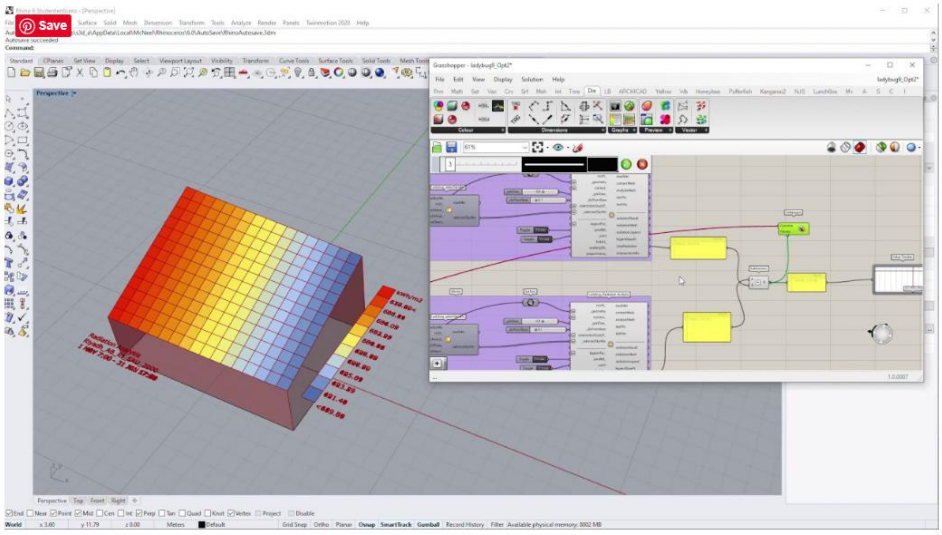


Figure 3-34: Ladybug, (Reference: parametric-architecture.com)

This tool is instrumental in sustainable design, helping professionals to assess the impact of natural elements on their designs and make informed decisions to optimize energy use, enhance comfort levels, and reduce the environmental footprint of their projects. By providing comprehensive environmental data analysis capabilities, Ladybug empowers users to integrate climate-responsive strategies into their design processes, promoting the creation of buildings and spaces that are more adaptive to their local environments (Ladybugtool.com 2022).

3.8.1.3 Honeybee

Honeybee is an environmental analysis plugin for Rhino, particularly used in conjunction with Grasshopper, Rhino's parametric design tool. It is designed to create, run, and visualize simulations related to building performance, focusing on daylighting and energy modelling. Honeybee integrates with Radiance, a lighting simulation tool, and Open Studio, an energy modelling tool, to allow users to assess the environmental impact and performance of their designs (Food4rgino.com).
The plugin helps architects and designers to analyse the energy consumption, thermal comfort, and lighting levels of buildings. This analysis can significantly influence the decision-making process in the early stages of design, enabling the creation of more energy-efficient and sustainable architectural projects. By providing detailed insights into the energy and lighting aspects of buildings, Honeybee supports the development of designs that are better adapted to their environments and more responsive to the needs of their occupants (Figure 3.13).

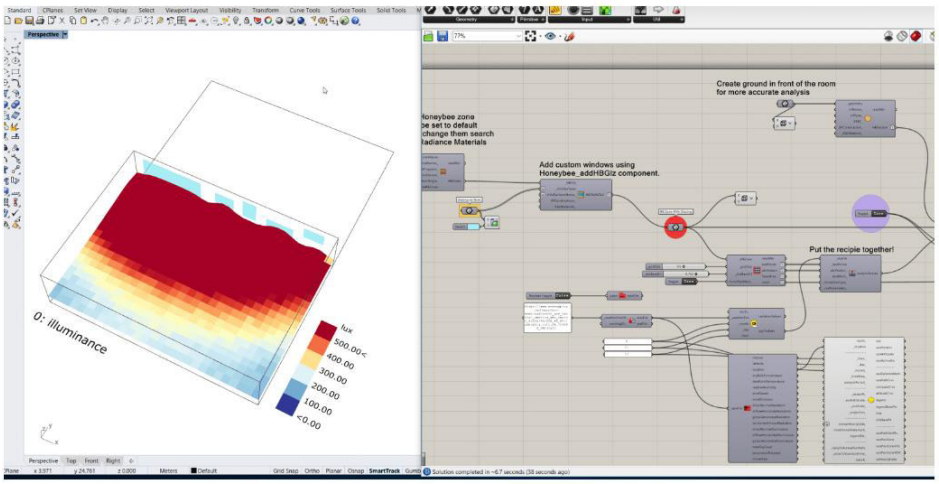


Figure 3-37: Honeybee, (Reference:parametric-architecture.co

3.8.1.4 One click lCA

One Click LCA is a plugin for Rhino designed to facilitate life-cycle assessment (LCA) within the architectural, engineering, and construction (AEC) sectors. It helps users to calculate the environmental impacts of their designs, focusing on metrics like carbon footprint, energy use, and resource consumption. This integration allows professionals to make more informed decisions regarding sustainability and to optimize their projects for better environmental performance (Figure 3.14).

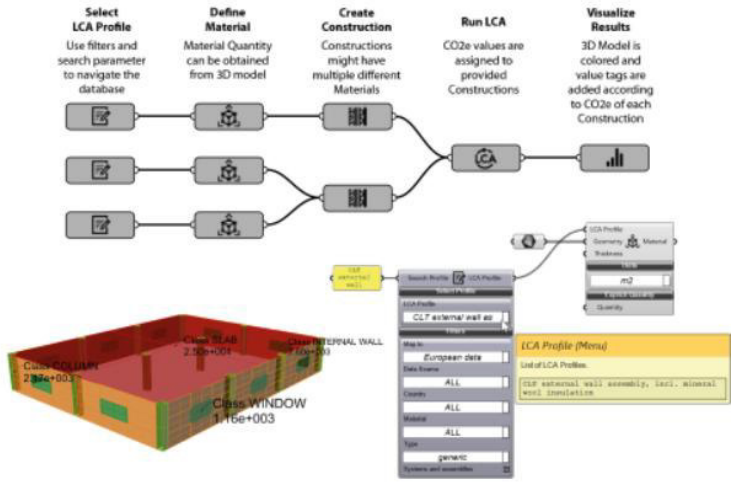


Figure 3-40: Oneclick lCA Plugin, (Reference: Food4rhino.com)

The plugin works within Rhino and Grasshopper, providing a seamless workflow for designers and engineers to analyse their models directly. Once installed, it appears in Grasshopper's plugin bar, making it easily accessible during the design process. One Click LCA aims to bring comprehensive LCA capabilities into the early stages of design, helping to embed sustainability into the project from the outset (Steven 2024). This approach supports the creation of more sustainable buildings by assessing and reducing their embodied carbon and other environmental impacts.

3.9 Comparative Analysis of Sustainability Frameworks in Boston and Italy

This section of the thesis explores the differences and similarities in sustainability practices, climate-responsive design, and positive buildings between Boston and Italy, focusing on the tools and strategies employed in each region. This comparative analysis aims to illuminate how distinct regional approaches are shaped by local contexts and regulatory environments, thereby enhancing our understanding of how contextual factors influence the effectiveness and implementation of sustainability strategies.

3.9.1 Regulatory and Legislative Frameworks:

The regulatory landscapes of Boston and Italy demonstrate significant differences in how sustainability is legally enforced and promoted. In Boston, state laws provide strong incentives for the adoption of clean energy solutions, exemplified by mandates like the installation of solar panels. These mandates are bolstered by substantial government investments in research and sustainable construction projects, reflecting a proactive approach to ecological challenges. In contrast, Italy's regulations often merge sustainability with heritage conservation, emphasizing the use of recycled and locally sourced materials. This approach is underpinned by European Union directives aimed at reducing carbon footprints and enhancing the sustainability of urban environments without compromising their historical integrity. Both regions illustrate diverse yet complementary models of legislative support for sustainable development,

offering valuable insights into the adaptability and replicability of these frameworks in varying cultural and economic contexts. Notably, the regulatory frameworks in Boston are perceived as more practical and have been more favorably received, suggesting a model that could potentially offer greater immediate efficacy in other urban contexts.

3.9.2 Certifications and Standards:

Sustainability certifications and ISO standards play pivotal roles in shaping sustainable practices in both Boston and Italy. In Boston, certifications such as LEED (Leadership in Energy and Environmental Design) are widely adopted, influencing major building projects to adhere to high standards of environmental performance. This adoption is supported by municipal policies that often require or incentivize certification, thus integrating these standards deeply into the local construction industry. Similarly, in Italy, the BREEAM (Building Research Establishment Environmental Assessment Method) and local equivalents like ITACA guide sustainable building practices, emphasizing not only energy efficiency but also the integration of cultural heritage preservation in building designs. Additionally, both regions adhere to ISO 14001, the international standard for environmental management systems, which provides a framework for organizations to enhance their environmental performance. The effective application of these standards and certifications in Boston and Italy demonstrates their potential as robust models for encouraging sustainable development in other urban environments globally. Their widespread acceptance and the tangible impacts they make on reducing environmental footprints underscore their replicability and adaptability in diverse regulatory and cultural landscapes.

3.9.3 Market Dynamics and Competition:

In the competitive landscape of Boston's construction and design industry, sustainability is not just a regulatory mandate but also a critical competitive edge. Companies vie for projects by showcasing their ability to meet and exceed the environmental performance benchmarks set by certifications such as LEED and standards like ISO 14001. This competition stimulates the market to adopt advanced sustainable technologies and innovative construction techniques, such as green roofing, energy-efficient glazing, and the use of materials with Environmental Product Declaration in new developments. Additionally, the push for higher sustainability ratings often drives firms to invest in research and development of new sustainable solutions, which further influences market dynamics. The effectiveness of these initiatives is visible in the increasing number of high-performance buildings and the proliferation of green technologies within the city. These developments not only fulfill regulatory requirements but also appeal to a growing demographic of environmentally conscious clients, thereby reshaping the market landscape and setting new industry standards.

3.9.4 Sustainability Elements in Design and Construction:

In Boston's construction and design industry, sustainable practices are deeply integrated into the fabric of urban development, particularly evident in the city's major building projects. These initiatives are characterized by several key sustainability elements that not only meet regulatory requirements but also set benchmarks for future developments:

- **Energy Efficiency**: Major projects in Boston often incorporate cutting-edge technologies such as geothermal heating and cooling systems and high-performance facades. These technologies are crucial in minimizing energy consumption and are a standard expectation in new developments aiming for high sustainability ratings.

- **Environmental Impact**: Compliance with LEED certification is widespread, driving the use of sustainable materials and construction techniques that significantly reduce the ecological footprint of buildings. Environmental Product Declarations (EPDs) play a critical role here, providing transparency about the environmental impact of materials used, which is crucial for informed decision-making in sustainable construction.

- **Indoor Environment Quality**: Enhancements aimed at improving indoor environmental quality, such as optimized natural daylighting and advanced air quality systems, are prioritized. These features not only enhance occupant comfort and health but also contribute to higher productivity and well-being, making them a staple in modern architectural design.

- **Innovative Technologies**: The integration of smart building technologies and renewable energy solutions is increasingly common. These technologies are not just add-ons but fundamental components that reflect Boston's commitment to leading-edge sustainable practices.

- **Transportation and Accessibility**: Sustainable transportation options are also a focus, with features like bike-friendly amenities and excellent public transport accessibility incorporated into project designs to minimize the carbon footprint associated with commuting.

These elements reflect Boston's comprehensive approach to sustainability, demonstrating the city's alignment with both environmental objectives and market demands. Such practices are not only about adhering to current standards but also about setting new precedents for urban development, underscoring the essential role of sustainable design experts in shaping the future of the built environment.

3.9.5 Cultural and Scientific Approaches to Sustainability:

Cultural attitudes towards recycling and sustainability exhibit notable differences between Boston and Italy, shaping the effectiveness of each region's sustainability practices. In Italy, the culture of recycling is deeply embedded within the community, with stringent separation of waste for recycling viewed as a civic duty. This contrasts sharply with Boston, where despite robust governmental efforts to promote recycling through enhanced infrastructure, public participation in such initiatives is somewhat lukewarm.

However, Boston shows a strong inclination towards renewable energy adoption, with many single-family homes investing in photovoltaic systems to harness solar energy. Additionally, innovative practices like rainwater harvesting for gardening purposes are increasingly popular among Boston residents, reflecting a growing cultural acceptance of sustainable living practices.

Scientifically, both regions leverage advanced methods and innovations in their approach to sustainability. In Boston, the application of cutting-edge technologies for energy efficiency and the integration of green infrastructure in urban planning are testaments to the city's scientific approach to environmental challenges. Meanwhile, Italy's focus on maintaining its cultural heritage while incorporating sustainable technologies offers valuable insights into balancing traditional practices with modern scientific innovations in sustainability.

These observations underline the significant role that cultural adaptation plays in the success of sustainability practices. While Italy benefits from a long-standing cultural commitment to recycling, Boston's scientific and technological advancements drive its sustainability efforts, pointing to the diverse ways in which cultural and scientific frameworks can influence environmental strategies.

3.9.6 Technology and Tools for Sustainability:

In the realm of sustainability, technology plays a pivotal role in evaluating and enhancing the environmental performance of building projects. Professional practices in Boston utilize a variety of software tools based on the specific aspects of sustainability being investigated. For instance, tools like OpenLCA, OneClick LCA, and Athena are extensively used for assessing environmental pollution throughout the lifecycle of a project. These tools enable precise calculations of environmental impact and are instrumental in helping architects and engineers design more sustainable solutions.

Moreover, the variety of software available extends beyond environmental impact assessment to include tools designed for specific sustainability applications. For instance, in educational settings, there is a strong emphasis on using simulation software to teach students about the indoor environmental quality of buildings, including software like EnergyPlus and Radiance for advanced lighting simulations. These tools not only help in the design phase but also provide students with hands-on experience in assessing and improving the sustainability of indoor environments.

The impact of these technological tools on sustainability outcomes is profound. By enabling detailed analysis and simulation, these tools allow for the optimization of designs from an environmental standpoint, directly influencing the sustainability of building projects. For example, lighting simulation software helps in optimizing natural light within a space, significantly reducing energy consumption for artificial lighting and enhancing the building's overall energy efficiency.

The diversity and specificity of these tools underscore their importance in advancing sustainability practices. They provide the necessary data and simulations that inform better decision-making, ensuring that sustainability is not just a concept but a practical, integral part of the development process. This technological integration into sustainability practices reflects a broader trend towards more scientifically rigorous and outcome-focused approaches in the field of sustainable architecture.

3.9.7 Renewable Energy and Resource Management:

In Boston, the integration of renewable energy sources into both new developments and existing structures is a critical component of the city's sustainability strategy. Solar panels, wind turbines, and geothermal systems are increasingly common features in

Boston's architectural landscape, supported by city policies that incentivize renewable energy installations. This proactive approach not only helps reduce the carbon footprint of buildings but also promotes energy independence.

Resource management in Boston involves sophisticated strategies to ensure efficient use of materials and resources throughout the lifecycle of construction projects. This includes the implementation of practices such as rainwater harvesting, extensive recycling protocols, and the use of sustainable materials that are locally sourced and manufactured. These practices are not merely about compliance with sustainability standards but are driven by a broader commitment to reducing environmental impact and enhancing the resilience of urban spaces.

The results of these initiatives vary, with renewable energy projects often leading to significant reductions in energy costs and greenhouse gas emissions. However, the implementation across different sectors and neighborhoods in Boston can be uneven, reflecting varying levels of investment and community engagement. This contrast highlights the challenges in scaling such practices city-wide, despite the clear environmental and economic benefits they offer.

By comparing these efforts with other cities or global standards, it becomes evident that Boston's integrated approach to renewable energy and resource management sets a benchmark for urban sustainability. However, it also underscores the need for continued innovation and community involvement to overcome barriers and achieve broader adoption of these crucial sustainability practices.

3.9.8 Recycling Practices:

In the realm of recycling, Italy and Boston present contrasting approaches that reflect their diverse cultural and regulatory landscapes. In Italy, recycling is not just a process of waste reduction but is integrated into the broader context of sustainable material management. The Italian approach emphasizes 'productive recycling,' where materials are repurposed in a manner that adds value—reflecting a deeply ingrained cultural practice supported by stringent European Union regulations. This approach is holistic, aiming not only to minimize waste but also to contribute to the economy by transforming recycled materials into valuable products.

Conversely, in Boston, while recycling initiatives are well-established, there remains ongoing debate about their environmental efficacy. Concerns center on the pollution generated by recycling processes themselves, such as emissions from transportation and processing facilities. These debates reflect broader cultural and institutional hesitancies, where the perceived environmental costs of recycling are weighed against its benefits. Factors contributing to this skepticism include a lack of stringent regulatory incentives compared to those in Italy and a cultural perspective that may not fully recognize the long-term sustainability benefits of aggressive recycling measures.

The effectiveness of recycling initiatives in both regions varies. Italy's comprehensive policies have led to high rates of recycling and public participation, largely due to widespread education about and commitment to environmental stewardship. In Boston, despite having the technological and infrastructural capacity, the effectiveness is mitigated by less cohesive public engagement and regulatory support.

Evaluating the replicability of these recycling practices in other contexts reveals complex challenges. Italy's model, reliant on cultural values and strong regulatory frameworks, may be difficult to replicate in regions without similar foundational supports. Boston's model, facing scrutiny over its environmental impact, highlights the need for robust policy alignment with scientific research to enhance the overall sustainability of recycling practices. Both models offer valuable lessons on the potential and limitations of recycling as a pillar of urban sustainability strategies.

3.9.9 Education and Training:

In the realm of education and training for sustainability in Boston, universities and educational institutions play pivotal roles in shaping the next generation of professionals. A notable feature of these educational approaches is the strong relationship between industry and academia, particularly emphasized in universities that foster regular interactions between students and firms.

For example, in many institutions, there are structured programs where weekly meetings with firms and factories are mandatory for students across various disciplines related to design and construction, such as architecture and structural engineering. These meetings are typically managed by graduate students and provide a platform for successful companies to share their practical experiences, challenges, and achievements. More importantly, they discuss areas where industry feels there is a lack of knowledge or skill among graduates, directly influencing curriculum adjustments and training programs to better align with real-world needs.

This approach not only bridges the gap between theoretical learning and practical application but also enhances the students' understanding of sustainability in real-world contexts. By engaging directly with industry leaders, students gain firsthand insights into the challenges and opportunities in implementing sustainable practices, which is crucial for their professional development.

Comparatively, the effectiveness and structure of such collaborations can vary significantly between regions. In some areas, the emphasis might be more on theoretical research with less frequent industry interaction, which can affect graduates' readiness to tackle practical sustainability challenges upon entering the workforce. In contrast, regions that emphasize practical engagement, like the described programs, often produce graduates who are more immediately capable of contributing to sustainability goals in their professional roles.

The implications of these educational approaches are significant. They not only prepare students to become more effective professionals but also ensure that the training they receive is closely aligned with the evolving demands of the industry. This is particularly important in fields like sustainability, where the pace of technological and methodological advancements is rapid, and the need for professionals who are both knowledgeable and adaptable is critical.

3.10 Impact of Boston Experience on Research Methodology

The author's experience in Boston has profoundly influenced the research methodology and framework developed in this chapter. The immersive learning environment at

Northeastern University, particularly the mentorship under Dr. Matthew Eckelman, provided a deep understanding of advanced life cycle assessment (LCA) methodologies and sustainable design principles. This exposure to state-of-the-art research and practical applications of sustainability directly shaped the holistic and evidence-based approach adopted in this thesis.

The insights gained from the "Sustainable Design and Technologies in Construction" course, under Professor David Fannon, enriched the author's knowledge of building rating systems such as LEED, BREEAM, and WELL. This education enabled the integration of standardized sustainability metrics into the research framework, ensuring that the proposed designs align with industry standards for environmental performance.

Furthermore, the hands-on project on Environmental Product Declarations (EPDs) underscored the importance of selecting materials based on their environmental impact, reinforcing the necessity of EPD-verified materials in the research prototype. This methodology ensured compliance with LEED standards and enhanced the accuracy of environmental performance analyses.

Overall, the Boston experience facilitated the integration of advanced sustainability tools and concepts into the research framework, enabling a comprehensive and robust methodological approach. This integration has been instrumental in developing a regenerative building design framework that emphasizes adaptability, reversibility, and long-term environmental sustainability.

3.11 Conclusion

This chapter establishes a regenerative building design framework that emphasizes adaptability and reversibility, fostering a positive environmental impact. This approach prioritizes maximizing the potential for future renovation, reuse, re-manufacturing, and recycling of buildings and their constituent parts. The integration of design elements with multi-performance criteria is paramount to simultaneously satisfy occupant needs for comfort and well-being while minimizing or even reversing the building's environmental impact. A holistic approach guides the selection of regenerative materials and products, emphasizing their residual value and reuse potential.

The regenerative design framework was chosen for its alignment with the objective of creating sustainable, adaptable, and environmentally restorative structures. Spatial structures lend themselves particularly well to this framework due to their parametric and environmentally responsive attributes. This alignment highlights the significance of spatial dynamics and material efficiency as integral components of regenerative design, contributing to long-term architectural sustainability. The incorporation of specialized software tools such as OpenLCA, Rhino, and related plugins supports this methodology. These tools facilitate comprehensive analysis and modeling of regenerative practices, substantiating the framework's viability and efficacy in accomplishing sustainable design objectives.

CHAPTER 4
Modeling and Analysis (Application of Tools)

Abstract

The research, like many others, commences with the exploration of two overarching questions. To address these questions effectively, the methodology is divided into two main steps. The study aims to investigate passive solutions for enhancing the sustainability of buildings, focusing on geometric design and material selection. The first step entails an examination of geometric aspects, while the second step delves into material considerations.

Formulating general questions serves as a guiding framework for the researcher to identify pertinent areas of investigation, while the methodology delineates how these questions will be addressed. Hypotheses, on the other hand, provide tentative insights into the anticipated outcomes of the research, serving as a positive envisioning of the research findings.

Goals serve to elucidate the overarching questions by articulating the specific motivations underlying their formulation. They clarify the rationale behind the research focus and the objectives sought to be achieved.

It is imperative to acknowledge that the life cycle stages pertinent to the modeling within this study are confined to the operational phase, denoted as B6. The research endeavor aims to critically appraise the significance of architectural form and material selection as passive design strategies during the operational period, with the intent of mitigating environmental impact. This will be accomplished through the quantification of energy consumption throughout the B6 stage. While it is recognized that material choice and geometric configuration exert substantial influence on other life cycle assessment stages (A and C), these stages fall beyond the scope of the current investigation and are suggested as focal points for future research endeavors.

The following flowchart provides a comprehensive view of the two-section methodology employed in this research to enhance understanding of the systematic approach adopted. It visually delineates the dual-phase structure, where each section corresponds to a distinct aspect of investigating passive solutions for building sustainability (Figure 4.1).

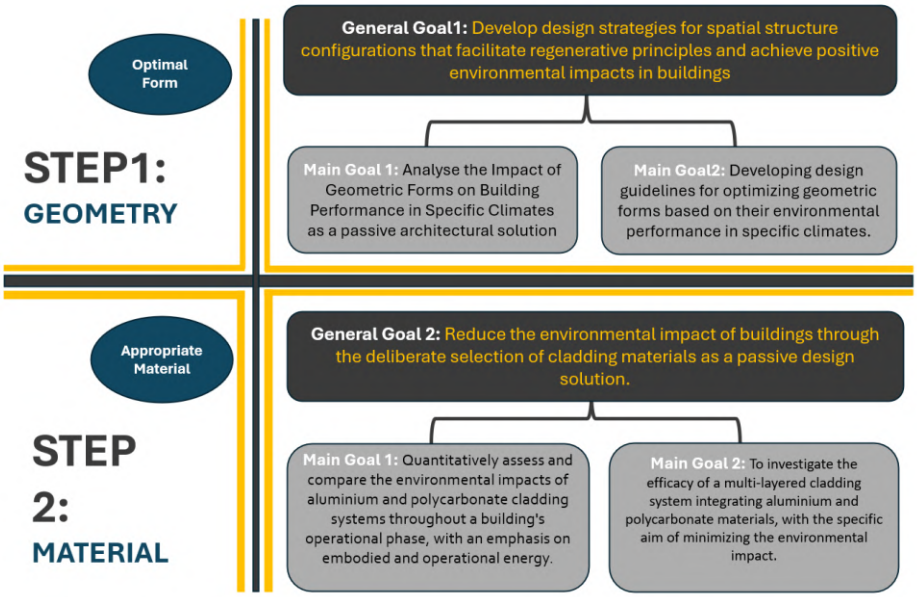


Figure 4-1: overall view of two methodology sections

Section 1: In this context, given the researcher's interest in investigating the impact of geometric design as a passive solution for sustainable buildings, the general question posed is: "How does the deliberate selection of geometric forms reduce the environmental impact of buildings?" The corresponding goal is to " Develop design strategies for spatial structure configurations that facilitate regenerative principles and achieve positive environmental impacts in buildings " The hypothesis posits that opting for climatically suitable forms with optimal dimensions will lead to reduced environmental impact through decreased energy consumption and material usage.
To systematically address the overarching objective, the researcher has delineated the broad aim into two distinct, pragmatic sub-goals. In pursuit of these targeted goals, the central research question has been bifurcated into two subsidiary inquiries. Herewith are detailed the specified primary objectives and the corresponding pivotal questions.

Main goal 1-1: Analyse the Impact of Geometric Forms on Building Performance in Specific Climates as a passive architectural solution.
Main goal 1-2: Developing design guidelines for optimizing geometric forms based on their environmental performance in specific climates.
The formulated goal serves as the impetus for seeking answers to the subsequent questions presented below.

Main question 1-1: To what extent do different geometric configurations affect the environmental performance of buildings in a specific climate?
To ascertain an appropriate methodology for addressing the primary research question, it was imperative to delineate specific, actionable questions. These practical inquiries have facilitated the researcher in identifying and selecting the most suitable methodological framework for the study. The practical questions are enumerated subsequently.
Practical questions:

- How is it possible to assess the environmental impact of geometry?
- Which software is the best to investigate the environmental impact of geometry?

- The biggest impact of geometry on environmental consequences may be found in which category?

Main question 1-2 : Do changing the dimensions will result the different environmental Impact?

Practical questions:

- How is it possible to assess the environmental impact of changing the dimensions of the Form?
- Which software is the best to investigate the environmental impact of changing the dimension of Forms a parametric variety?
- Which geometric dimension has the greatest influence on a building's environmental impact?

To provide further clarity and practicality, it becomes imperative to refine these general concepts into specific and actionable research inquiries. The subsequent flowchart illustrates the main question alongside its associated sub-questions, facilitating a structured and comprehensive approach to addressing the research objectives (Figure 4.2).

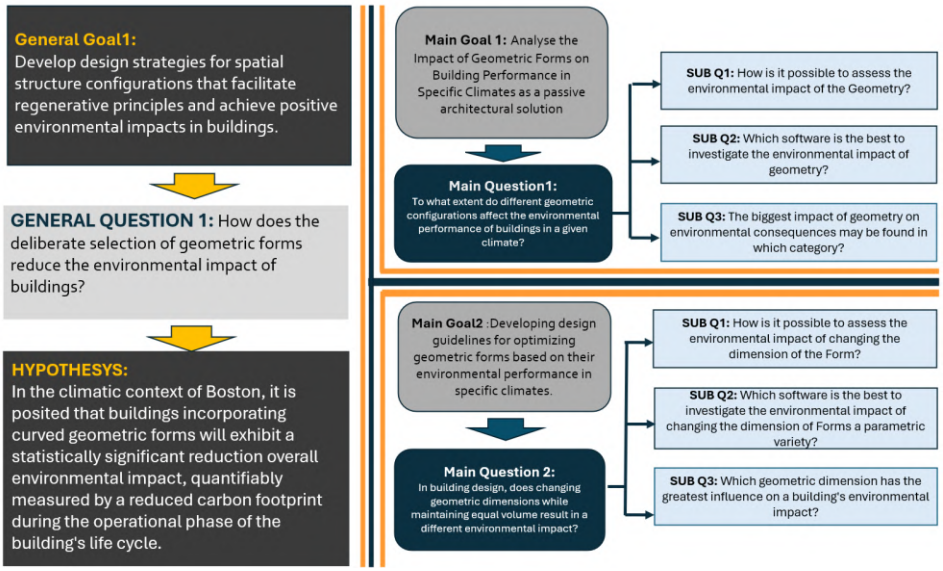


Figure 4-4: Question, Goals, and Hypothesis in Section 1

In line with customary research endeavors, the researcher encountered various challenges in addressing the formulated questions. Addressing these challenges necessitated innovative and creative approaches in the research process. One such challenge pertained to elucidating methodologies for modeling and investigating the influence of geometric parameters.

Primarily, the initial approach involved quantifying the material requirements for constructing and configuring diverse geometric forms and structures. This approach stems from the recognition that materials play a pivotal role in determining the environmental footprint of buildings and constructions. However, it is noteworthy that numerous studies have extensively explored the environmental impact attributable to materials across different stages of a building's life cycle. Nonetheless, the researcher aimed to unearth architectural principles that could serve as passive solutions, underscoring the imperative to integrate elements of innovation and creativity into the research framework.

A secondary challenge revolved around identifying software tools that could facilitate the research objectives effectively. Through a comprehensive review of the literature and an analysis of existing research endeavors, it was discerned that one viable avenue for assessing the environmental impact arising from geometric considerations entailed quantifying energy consumption during the operational phase. This strategic shift in focus underscores the researcher's commitment to employing methodologies that offer nuanced insights into the environmental ramifications of geometric design choices.

Section 2: In the forthcoming segment of the investigation, the environmental repercussions associated with various cladding systems will be scrutinized. The inquiry will be guided by the fundamental question: **"How can strategic cladding material choices minimize the environmental impact of buildings? "**This question aligns with the overarching aim to **"Reduce the environmental impact of buildings through the deliberate selection of cladding materials as a passive design solution."** The hypothesis posits that by altering the thickness and elucidating the parametric interrelations among the layers of the cladding system, one can devise methodologies to reduce the environmental detriment caused by edifices. Although material utilization inevitably engenders environmental effects, the focus of this segment is to compare disparate cladding systems and evaluate the extent to which environmental impacts can be lessened through judicious selection.
The selection of materials for this study was rigorously conducted with a preference for those possessing Environmental Product Declaration (EPD) certifications. This strategic choice ensures that the environmental impacts associated with these materials during phases A and C have been comprehensively assessed and documented. Consequently, the primary objective of this research is to concentrate on evaluating the environmental implications within the B6 stage. This focus allows for a more targeted investigation into the sustainable performance and potential environmental benefits of utilizing EPD-certified materials in this specific phase of the product lifecycle.
To methodically approach the principal aim, the investigator has segmented the comprehensive goal into two separate and concrete sub-objectives. To achieve these specified goals, the main research query has been divided into a pair of subordinate questions. Presented hereafter are the outlined main objectives along with their associated crucial questions.
Main Goal 2-1: Quantitatively assess and compare the environmental impacts of aluminum and polycarbonate cladding systems throughout a building's operational phase, with an emphasis on embodied and operational energy.
Main Goal 2-2: To investigate the efficacy of a multi-layered cladding system integrating aluminum and polycarbonate materials with the specific aim of minimizing the environmental impact and increasing sustainability.

The established goal acts as a catalyst for the pursuit of responses to the ensuing inquiries delineated beneath.

Main question 2-1: Considering operational energy carbon footprint, which is more sustainable for building cladding: aluminium or polycarbonate?

Like Section 1, in Section 2 as well, it was essential to formulate precise, implementable questions to guide the selection of an effective methodology for the research question at hand. These pragmatic questions have assisted the researcher in the discernment and choice of an appropriate methodological structure for the analysis. The specific questions will be listed in the below:

Practical questions:

- The biggest impact of cladding environmental consequences may be found in which category?
- Which layer of cladding had caused more environmental impact in per category impacts?
- Changing the thickness of different layers of the aluminum cladding system will affect on which environmental category more?
- Changing the physical features of polycarbonate Will effect on which environmental impact category more?

Main question 2-2: how does a combined cladding system model influence the environmental Impact of Buildings and sustainability?

- What are the comparative environmental impacts of buildings with combined cladding systems versus those with single-material cladding systems?
- How do the implementation requirements of combined cladding systems impact the long-term environmental sustainability of building structures?
-

For a clear and practical research plan, it needs to turn broad concepts into focused research questions. The flowchart below shows how the main question breaks down into smaller, easier-to-address sub-questions (Figure 4.3).

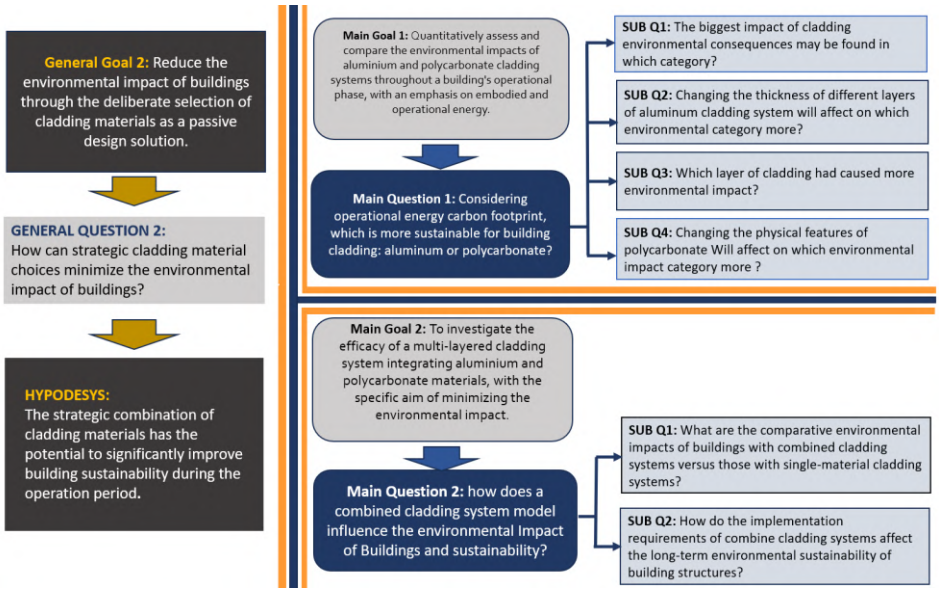


Figure 4-7: Question, Goals, and Hypothesis in Section 2

Diagram 4.1 illustrates the systematic arrangement and structural composition of Chapter 4 and 5, delineating the workflow and methodological approach undertaken in this segment of the research. It provides a visual representation of the sequence in which the chapter unfolds, highlighting the key components and their interrelations within the overall narrative.

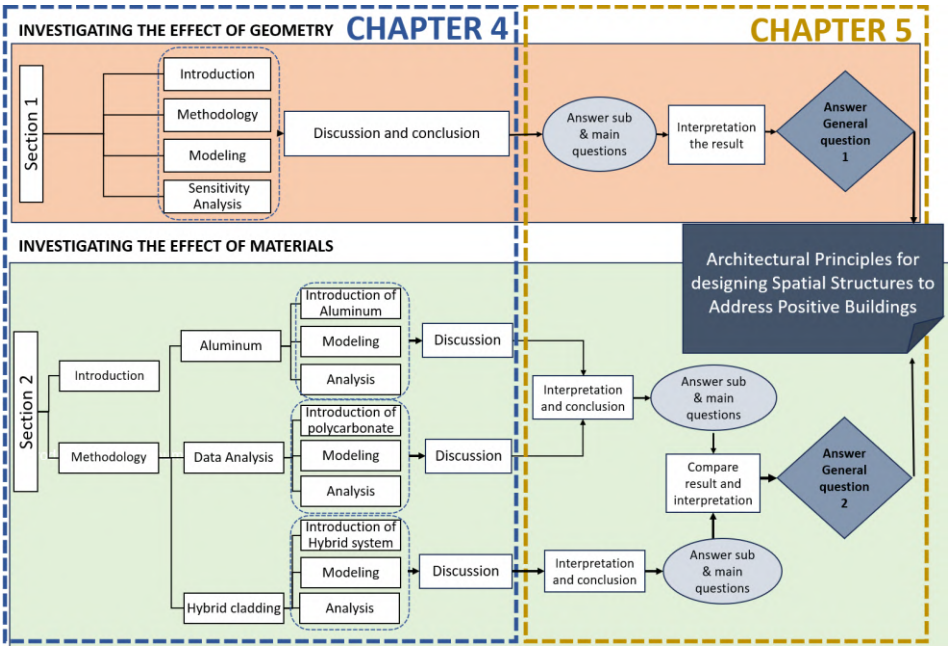


Diagram 4-2: Methodological Process and Workflow, Appendix C, Page395

This diagram serves as a roadmap, guiding the reader through the logical progression of the chapter, from the initial conceptual framework to the empirical analysis and subsequent discussion of findings. It encapsulates the methodical process employed to address the research questions, showcasing the step-by-step procedure that underpins the investigative journey.

Moreover, Diagram 7 elucidates the methodological rigor and comprehensive planning inherent in the research design, thereby underscoring the academic integrity and scholarly depth of the study. Through this visual aid, the coherence and systematic nature of the research process is accentuated, facilitating a clearer understanding of the methodological underpinnings and the sequential logic that guides the chapter's development.

The following section presents an in-depth examination of the fundamental principles underlying the achievement of the primary objective. This exploration will be followed by a comprehensive elucidation of the research methodology utilized in this study.

4.1 Section 1: Geometry

4.1.1 Introduction

The built environment plays a significant role in environmental pollution. With geometric design holding a central role in architecture, understanding its direct impact on environmental health is crucial. While research has explored geometry's effects on material usage and energy efficiency, the precise modeling and quantification of pollution caused by varying building geometries remain a critical area of study for sustainable design.

This investigation aims to compare the environmental impacts of different geometries, evaluating the pollution caused by various building geometries. By systematically modeling three distinct parametric geometries, this section will delve into a comparative analysis of their environmental implications, focusing on aspects such as energy consumption, resource efficiency, and waste generation. The findings will directly inform environmentally conscious architectural design practices, offering a nuanced understanding of how geometry influences sustainability.

This research offers the potential to provide architects and designers with the tools to make informed geometric decisions that directly minimize environmental pollution. Such knowledge empowers the design of future built environments that work to alleviate, rather than contribute to, environmental harm. It bridges the gap between theoretical design principles and practical environmental outcomes, fostering a holistic approach to sustainable architecture that is critically informed by empirical evidence and analytical rigor.

4.1.2 Methodology

In this research, the researcher focus on a case study involving a large office prototype located in Boston. the researcher conducted a comparative analysis of three distinct simple geometric shapes - a cube, a sphere, and a cask - to evaluate their respective environmental impacts. This assessment primarily focused on the environmental repercussions attributable to energy consumption during the operational phase (B6), specifically for heating and cooling purposes per meter square. To facilitate this analysis, researcher utilized parametric modeling techniques in Grasshopper, a graphical algorithm editor integrated with Rhino's 3D modeling tools. The environmental assessment was enriched by incorporating climate data through the implementation of Honeybee and Ladybug, plugins for Grasshopper that enable environmental analysis. The city of Boston was selected as the geographical context for this case study. Each geometric shape underwent extensive modeling iterations, exceeding 2000 simulations, to ensure a comprehensive analysis. For the assessment of the life cycle impacts, the OpenLCA framework was employed. This involved modeling the process of low-voltage electricity generation in Boston, calibrated to a unit of one kilowatt-hour. In terms of spatial dimensions, the minimum and maximum areas considered for each shape were 100 square meters and 2500 square meters, respectively. Similarly, the volume parameters ranged from a minimum of 380 cubic meters to a maximum of 47,000 cubic meters. Lastly, to conduct a sensitivity analysis, was applied the Python programming language, leveraging its robust analytical capabilities to scrutinize the data and infer meaningful insights. Figure 4.4 illustrates a flowchart of research methodology.

Notice: The modeling process was executed across two distinct scenarios. In the initial scenario, the Rhino software's default settings were employed, which dictated that for crusts with angles less than 60 degrees, the default ceiling material would be utilized, while for crusts exceeding an angle of 60 degrees, the default wall materials were applied. Conversely, in the second scenario, all crusts were uniformly classified as roofing, and the materials designated for geometric design were uniformly adopted as the default roofing materials. It is essential to highlight that the analysis was aimed at comparing different geometrical configurations rather than precisely quantifying energy consumption. As a result, the influence of materials on energy utilization was minimal, thereby justifying the decision to apply the same material across all geometric designs.

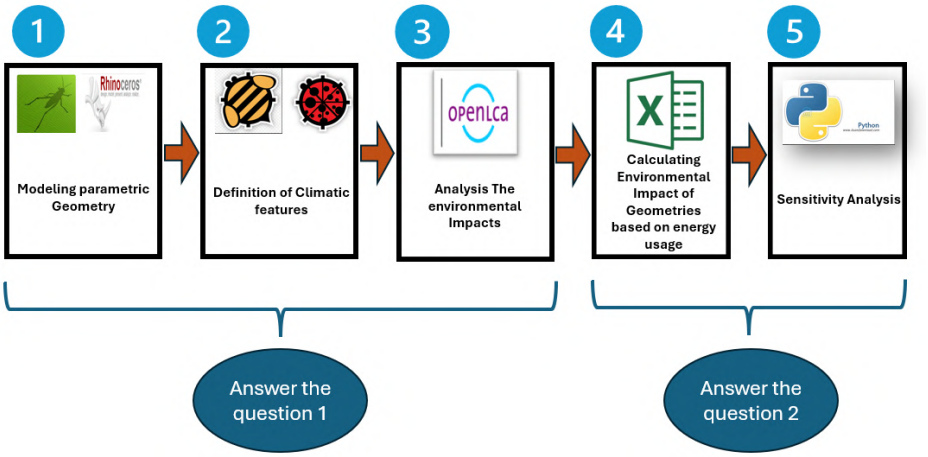


Figure 4-10: Schematic Representation of Methodology Steps

4.1.3 Modeling Geometries (Step 1&2)

The modeling process was executed in Rhino, where each geometric form was analyzed independently to ensure detailed scrutiny. The following will elucidate all levels of the modeling phase, encompassing the creation, analysis, and interpretation of each geometric shape.

Initially, parametric designs for the cube, sphere, and cylinder were constructed in Rhino, leveraging its advanced 3D modeling capabilities. This step involved defining the dimensions and proportions of each geometry to align with the specified criteria for the large office prototype. Subsequently, these models were imported into Grasshopper, where parametric variables were systematically manipulated to generate a wide range of design iterations. This approach enabled the exploration of the geometries' performance under various configurations and conditions.

In the analysis phase, each model was subjected to environmental simulations using the Honeybee and Ladybug plugins, which facilitated comprehensive evaluations of energy consumption, thermal performance, and overall sustainability metrics. The simulations were calibrated to reflect the climatic data of Boston, ensuring that the results were contextually relevant and accurate.

As illustrated in Figure 4.5, the variables for a cube are in the X, Y, and Z directions, corresponding to length, width, and height, respectively. For a sphere, the variables are reduced to radius and height. In the case of a cask, the relevant variables are length, height, and radius. Regarding comfort conditions, ASHRAE standards have been adopted for Boston. The function of the buildings under consideration is that of large

offices. The HVAC systems have been standardized across all geometrical configurations, thereby neutralizing the impact of system size on the overall analysis. While the energy consumption of cooling and heating systems has been considered, it is important to note that the electricity usage for lighting and other facilities is largely contingent on user behavior. Consequently, to simplify the variables under consideration and focus on the primary energy drivers, these user-dependent factors have been excluded from the analysis for all shapes, thereby reducing the number of variables to a manageable extent. However, the analysis conducted across both scenarios yielded identical outcomes with respect to the comparative assessment of energy savings achieved through various geometric configurations.

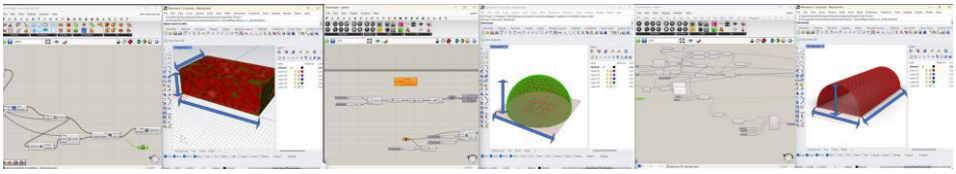


Figure 4-13: Modelling in Grasshopper, (Reference: Author)

4.1.3.1 Sphere data:

The variety of parameters for a sphere include Radius and Height. The minimum surface area is approximately 100 square meters, while the maximum surface area is roughly 2500 square meters. The minimum volume is around 376 cubic meters, and the maximum volume approaches 47000 cubic meters. A total of 1700 models for spheres were developed (Figure 4.6).

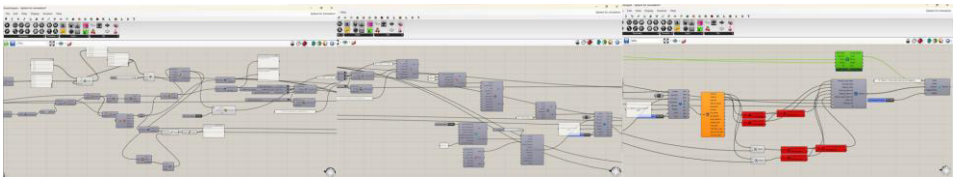


Figure 4-16: The process of sphere modeling in the Grasshopper, (Reference: Author)

At this stage, the output data encompasses cooling, heating, and the total thermal energy per kilowatt-hour. Table 4.1 displays the output results after modeling and analysis conducted using Grasshopper, Honeybee, and Ladybug.

in:Radius	in:Height	out:Thermal Load (kWh)	out:Cooling (kWh)	out:Heating (kWh)	out:Cooling (kWh/m2)	out:Heating (kWh/m2)	out:Thermal Load (kWh/m2)	out:Area (m2)	out:Volume (m3)	out:H
5.7	0.93	6949.507445	289.871688	6659.635757	2.890407	66.405447	69.295854	100.287493	377.749552	5.2545
5.7	0.82	6595.02943	279.982333	6315.047097	2.791797	62.969438	65.761236	100.287493	377.749552	4.633
5.7	0.75	6402.695557	275.190718	6127.504838	2.744018	61.099392	63.84341	100.287493	377.749552	4.2375
5.7	1	7196.283853	298.236157	6898.047695	2.973812	68.782732	71.756544	100.287493	377.749552	5.65
5.7	0.73	6340.584574	273.713552	6066.871022	2.729289	60.494792	63.224081	100.287493	377.749552	4.1245
5.7	0.79	6527.913729	279.136991	6248.776737	2.783368	62.308635	65.092003	100.287493	377.749552	4.4635
5.7	0.94	6982.486747	290.783281	6691.703465	2.899497	66.725205	69.624702	100.287493	377.749552	5.311
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
28	0.75	157166.2451	5967.990964	151198.2542	2.387108	60.477068	62.864176	2500.092345	47018.4029	21.1575
28	1	177435.7777	6539.884122	170895.8936	2.615857	68.355832	70.97169	2500.092345	47018.4029	28.21
28	0.73	156342.3039	5991.474794	150350.8291	2.396501	60.13811	62.534612	2500.092345	47018.4029	20.5933
28	0.79	160964.4442	6142.012829	154822.4314	2.456714	61.926685	64.383399	2500.092345	47018.4029	22.2859
28	0.94	172051.6662	6349.843038	165701.8232	2.539843	66.278281	68.818124	2500.092345	47018.4029	26.5174
28	0.83	164123.491	6253.141384	157870.3497	2.501164	63.145807	65.646972	2500.092345	47018.4029	23.4143
28	0.77	159415.5949	6072.719092	153342.8758	2.428998	61.334885	63.763883	2500.092345	47018.4029	21.7217
28	0.7	150065.3494	5676.04587	144389.3036	2.270334	57.753588	60.023923	2500.092345	47018.4029	19.747
28	0.93	171251.7754	6339.24358	164912.5318	2.535604	65.962576	68.49818	2500.092345	47018.4029	26.2353
28	0.71	150797.0872	5711.561922	145085.5253	2.28454	58.032067	60.316607	2500.092345	47018.4029	20.0291
28	0.7	150065.3494	5676.04587	144389.3036	2.270334	57.753588	60.023923	2500.092345	47018.4029	19.747

Table 4-2: Input and output results after modeling sphere, Appendix D, Page 455

4.1.3.2 Cube Data:

The parameters for a cube include Length (X), Width (Y), and Height (Z). Despite the change in shape from a sphere to a cube, the surface area and volume metrics are retained. The minimum surface area remains approximately 100 square meters, and the maximum surface area is around 2500 square meters. Similarly, the minimum volume is about 376 cubic meters, and the maximum volume is close to 47000 cubic meters. A total of 170000 models for cubes were developed (Figure 4.7).

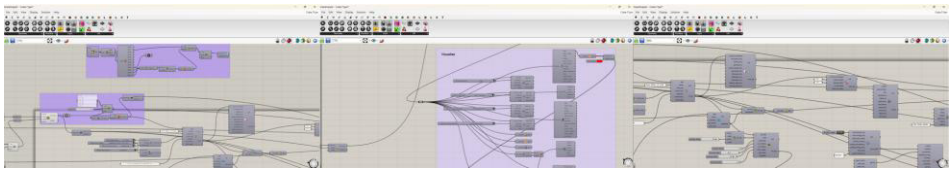


Figure 4-19: The process of Cube modeling in the Grasshopper, (reference: Author)

At this stage, the output data include cooling, heating, and the total thermal energy per kilowatt-hour. Table 4.2 displays the output results after modeling and analysis conducted using Grasshopper, Honeybee, and Ladybug.

in:Length (x)	in:Width (Y)	in:Height (Z)	out:Thermal Load (kWh)	out:Cooling (kWh)	out:Heating (kWh)	out:Cooling (kWh/m2)	out:Heating (kWh/m2)	out:Thermal Load (kWh/m2)	out:Area (m2)	out:Volume (m3)
10.45	10	3.76	9010.651	363.7439	8646.907	3.480803	82.74552	86.22632	104.5	392.92
10.45	10	5.64	11218.36	453.7968	10764.57	4.342553	103.0102	107.3528	104.5	589.38
10.45	10	7.52	13456.05	545.7781	12910.27	5.222757	123.5433	128.766	104.5	785.84
10.45	10	9.4	15705.53	636.2469	15069.28	6.088487	144.2037	150.2922	104.5	982.3
10.45	10	11.28	17972.86	732.6531	17240.2	7.011034	164.978	171.9891	104.5	1178.76
10.45	10	13.16	20252.38	831.259	19421.12	7.954631	185.8481	193.8027	104.5	1375.22
10.45	10	15.04	22535.08	925.1609	21609.92	8.853214	206.7935	215.6467	104.5	1571.68
10.45	10	16.92	24822.2	1018.45	23803.75	9.74593	227.7871	237.533	104.5	1768.14
10.45	10	18.8	27114.79	1111.681	26003.11	10.6381	248.8336	259.4717	104.5	1964.6
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
49.4	49.91	13.16	182629.8	6728.834	175900.9	2.729137	71.34337	74.07251	2465.554	32446.69
49.4	49.91	15.04	193173.6	7242.721	185930.9	2.937563	75.41139	78.34896	2465.554	37081.93
49.4	49.91	16.92	203649	7590.866	196058.1	3.078767	79.5189	82.59766	2465.554	41717.17
49.4	49.91	18.8	214112.3	7871.435	206240.8	3.192562	83.64888	86.84144	2465.554	46352.42

Table 4-5: input and output results after modeling cube, Appendix D, Page 456

4.1.3.3 Cask Data

The specifications for a cask encompass Radius, Height, and Length. Despite transitioning from the geometric shape of a sphere to a cask, we retain the same metrics for surface area and volume. The surface area ranges from a minimum of approximately 100 square meters to a maximum of around 2500 square meters. Similarly, the volume extends from a minimum of about 376 cubic meters to a maximum of close to 47000 cubic meters (Figure 4.8).



Figure 4-22: the process of Caske modeling in the Grasshopper, (Reference: Author, ABITA lab)

A comprehensive suite of 1700 models for casks has been developed. At this point, the analyzed output data includes cooling, heating, and the total thermal energy consumption per kilowatt-hour. Table 4.3 presents the outcomes after modeling and analysis using Grasshopper, Honeybee, and Ladybug.

in:Radius	in:Length (Y)	in:Height (Z)	out:Thermal Load (kWh)	out:Cooling (kWh)	out:Heating (kWh)	out:Cooling (kWh/m2)	out:Heating (kWh/m2)	out:Thermal Load (kWh/m2)	out:Area (m2)	out:Volume (m3)
5	10	1	8264.148	335.9719	7928.176	3.359719	79.28177	82.64148	100	392.6991
5	10	1.045	8329.703	188.8629	8140.84	1.888629	81.4084	83.29703	100	410.3705
5	10	1.061	8412.522	191.3434	8221.179	1.913434	82.21179	84.12522	100	416.6537
5	10	1.033	8417.13	342.3111	8074.819	3.423111	80.74819	84.1713	100	405.6582
5	10	1.081	8504.693	184.2168	8320.477	1.842168	83.20477	85.04693	100	424.5077
5	10	1.089	8572.387	203.7886	8368.598	2.037886	83.68598	85.72387	100	427.6493
5	10	1.16	8839.479	174.5891	8664.89	1.745891	86.6489	88.39479	100	455.5309
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
20	62.497	1.081	192984.8	7333.867	185650.9	2.933688	74.26394	77.19763	2499.88	42448.73
20	62.497	1.089	193339.4	7336.677	186002.7	2.934812	74.40465	77.33947	2499.88	42762.88
20	62.497	1.16	195020.9	3926.836	191094.1	1.57081	76.4413	78.01211	2499.88	45550.91
20	62.497	1.197	198929.2	3898.682	195030.5	1.559548	78.01596	79.57551	2499.88	47003.82
20	62.497	1.154	199803.8	7536.741	192267.1	3.014841	76.91052	79.92537	2499.88	45315.3
20	62.497	1.2	203630.5	7642.311	195988.1	3.057071	78.39902	81.45609	2499.88	47121.63

Table 4-8: input and output results after modeling Caske, Appendix D, Page456

4.1.4 Modeling in OpenLCA (Step3)

In the OpenLCA framework, the dataset titled 'Market for Electricity, Low Voltage | Electricity, Low Voltage | Cutoff, U' has been utilized. This specific dataset encapsulates the characteristics of electricity available at the low voltage level within the Northeast Power Coordinating Council region of the United States, pertaining to the year 2014. It effectively illustrates the transmission process of 1 kWh of electricity at this low voltage level. Furthermore, the dataset delineates the proportional contributions of various electricity technologies to this market as they stood in the year 2016. This analytical process commences with the input of 1 kWh of electricity into the low voltage transmission network. The endpoint of this process is defined as the conveyance of 1 kWh of low voltage electricity through the transmission network, utilizing both aerial lines and cables. The TRACI 2.1 methodology serves as the impact assessment tool employed in this analysis. The Ecoinvent database provides the necessary underlying data. For this study, the defined functional unit is 1 kilowatt-hour, while the system boundary encompasses electricity generation, transmission, and distribution phases. The subsequent results elucidate the environmental impact associated with the production, transmission, and distribution of 1 kWh of low-voltage electricity in the Boston area (Table 4.4).

Impact category	Reference unit	Result
Fossil fuel depletion	MJ surplus	0.497635447
Global warming	kg CO2 eq	0.233240495
Ecotoxicity	CTUe	0.200677104
Smog	kg O3 eq	0.005114277
Acidification	kg SO2 eq	0.000411533
Eutrophication	kg N eq	0.000133957
Respiratory effects	kg PM2.5 eq	4.94753E-05
Ozone depletion	kg CFC-11 eq	2.91448E-08
Non carcinogenics	CTUh	7.85226E-09
Carcinogenics	CTUh	1.7759E-09

Table 4-10; The environmental Impact categories, Appendix D, page 457

4.1.4.1 Normalization Data based on Co2 Kg equivalent:

The normalized results give the ratio of the specific environmental impact to the global warming impact, expressed in equivalent kilograms of CO_2.The normalization process for the environmental impact data based on CO_2 equivalence involves several steps:

Identify the Normalization Factors: there is a set of normalization factors for each environmental impact category. These factors are derived from a reference dataset (in this case, from the US 2008 inventory data using openLCA, ecoivent 3.6).

Acidification: 94.5501751778371,
Carcinogenics: 4.97525060101256E-5,
Ecotoxicity": 10975.0810784115,
Eutrophication: 20.7257919485728,
Fossil fuel depletion": 21286.9221664978,
Global warming: 24038.981612583,
Non carcinogenics: 0.00103279209996221,
Ozone depletion": 0.145783649998144,
Respiratory effects: 29.5590347721844,

Smog": 1447.95751113479

Calculate the CO_2 Equivalence: To find the CO_2 equivalence for each category, it should divide the result for that category by its respective normalization factor. This step adjusts the raw environmental impact data, so it is comparable across different categories.

Determine the Reference Category for CO_2: it should use the category of 'Global Warming' as the reference for CO_2 equivalence since it is directly measured in kg CO_2 eq.

Normalize Based on CO_2 Equivalence: To normalize the impacts based on CO_2, it first needs to calculate the normalized value for the 'Global Warming' category using its normalization factor. Then should divide the CO_2 equivalence of all other categories by the normalized CO_2 equivalence of the 'Global Warming' category. This gives us a relative scale where the impact of 'Global Warming' is 1, and all other impacts are scaled accordingly.

Therefore base on the above explanation, The normalized results give the ratio of the specific environmental impact to the global warming impact, expressed in equivalent kilograms of CO_2. The normalization factor for global warming based on US 2008 inventory data (openlca ecoinvent 3.6) is 24038.981612583 kg CO_2 eq. The following calculation shows the normalization for per category based on the following formulation: $\text{Normalized Impact} = \frac{\text{Impact Result}}{\text{Normalization Factor}}$

To ascertain the most critical or 'dangerous' categories from an environmental impact standpoint, the magnitude of the impact values was taken into consideration. Below is a qualitative assessment predicated on the acquired data:

Fossil Fuel Depletion is marked by the most substantial normalized CO_2 equivalent impact, which is 2.409 times that of Global Warming. The actual environmental result for Fossil Fuel Depletion is 0.497635 MJ surplus. This high normalized value signifies an environmental concern of considerable magnitude, highlighting the urgent need to reduce reliance on non-renewable energy sources and their significant contribution to CO_2 emission

Global Warming Potential is assessed at 0.233240 kg CO_2 eq, which serves as the baseline for our CO_2 equivalence with a normalized value of 1.000. This signifies the direct contribution to climate change through greenhouse gas emissions associated with electricity production. The central position of this category emphasizes the critical need for climate change mitigation strategies within the energy sector.

Ecotoxicity, with a result of 0.200677 CTUe, has a normalized CO_2 equivalent impact of 1.885, reflecting the potentially harmful effects on ecosystems due to toxic pollutants released. This impact is vital for evaluating the broader ecological consequences of electricity generation and underlines the necessity for employing cleaner production technologies.

Smog formation is indicated by 0.005114 kg O_3 eq with a normalized CO_2 equivalent impact of 0.364. Despite being lower in normalized CO_2 equivalence compared to other categories, it remains a notable environmental health concern, especially regarding air quality and respiratory health risks, particularly in urban settings.

Non-carcinogenic and Carcinogenic impacts, with normalized CO_2 equivalent impacts of 0.784 and 3.679 respectively, indicate the potential for causing non-cancerous and cancerous health effects from chemical exposure. While these values are low, they still accentuate the ongoing need to manage and monitor toxic substances in the energy sector to safeguard public health.

Eutrophication, with a normalized CO_2 equivalent impact of 0.666, reflects the process by which water bodies become overly enriched with nutrients, potentially leading to excessive algal growth and oxygen depletion. Despite its relatively minor normalized impact, this highlights the importance of controlling nitrogen emissions and runoff from energy production facilities.

Ozone Depletion, with a negligible normalized CO_2 equivalent impact of 0.021, indicates a minimal impact on the stratospheric ozone layer from this specific source of electricity generation. Nonetheless, the importance of monitoring this category remains due to the long-term and global effects of ozone layer depletion on UV radiation levels.

Acidification, with a normalized CO_2 equivalent impact of 0.449, is associated with the release of sulfur dioxide and similar compounds, which can lead to acid rain, impacting soil, water bodies, and biodiversity. Although this impact is less when normalized compared to categories like fossil fuel depletion and global warming, it still underscores the need for sulfur emission controls in the electricity generation process.

Respiratory Effects, with a normalized CO_2 equivalent impact of 0.173, relate to health implications due to particulate matter smaller than 2.5 micrometers. Despite its lower normalized numerical impact, the health implications are of critical environmental concern, particularly in densely populated or industrial areas. Diagram 4.2 shows the different flow contributions in per category. Each category's CO_2_eq value is derived by contextualizing the specific impact in terms of CO_2 equivalent emissions, providing a common ground for comparison across different environmental impacts. These analyses underscore the multifaceted nature of environmental impacts associated with electricity generation, emphasizing the importance of adopting comprehensive strategies for reducing ecological footprints and protecting both ecosystems and human health (Diagram 4.2).

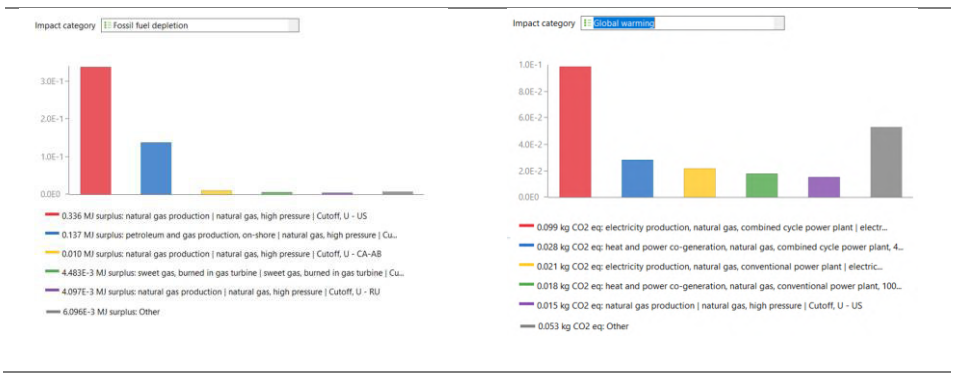
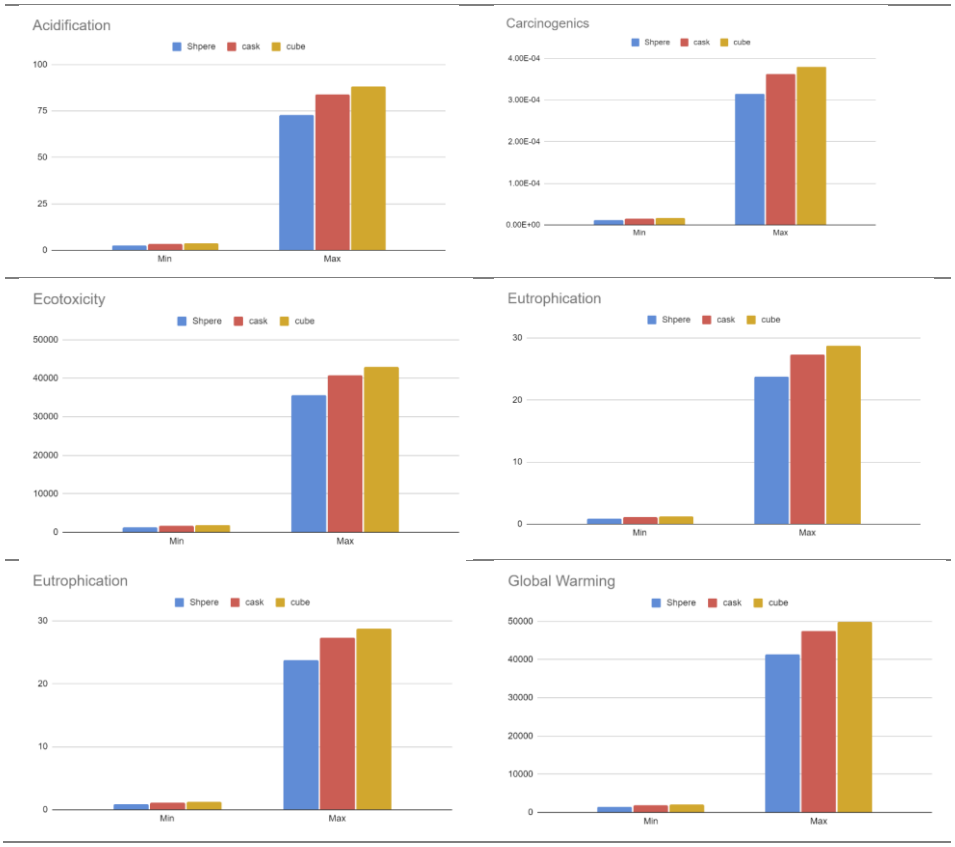




Diagram 4-5: the different flows contribution in per category, Appendix C, Page 395

4.1.5 Calculating environmental impact caused by different Geometries (Step4)

At this juncture, the analytical output derived from the Grasshopper framework quantitatively illustrates the energy consumption required to maintain comfort conditions per square meter for both cooling and heating. Consequently, the researcher has extrapolated these results to ascertain the cumulative environmental impact attributable to each geometrical configuration under study. The primary objective of this research was to identify the most environmentally optimal geometric configuration. At this phase of analysis, comparative data has been meticulously evaluated. In an analysis of energy consumption for cooling and heating to achieve comfort conditions in buildings of three different geometries (cube, sphere, and cask) in the city of Boston, the data reveals noteworthy efficiencies associated with the spherical shape. The comparison focused on the average kilowatt-hour (kWh) consumption required for cooling and heating across each shape, with the intention of identifying the most energy-efficient geometry. The sphere, cube, and cask configurations were evaluated under identical minimum and maximum area and volume conditions to ensure a fair assessment. After conducting an analysis of the environmental impacts induced by various geometric shapes, a comparative assessment between these geometries was undertaken to evaluate their respective footprints across all environmental categories. The findings indicate that consistently across all assessed categories, the sphere demonstrates the most favorable environmental performance. This implies that considering both the minimum and maximum environmental impacts per category, the sphere consistently exhibits the lowest environmental impact among the three shapes evaluated. (Diagram 4.3)



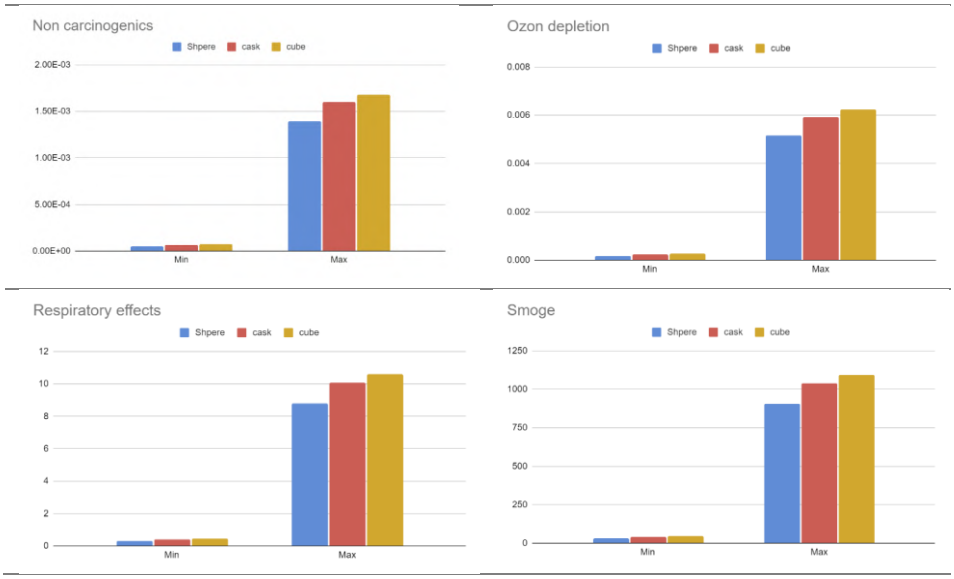


Diagram 4-8: comparison environmental impact of different, geometries, Appendix C, Page 397

The findings indicate that the sphere is approximately 0.79% more energy-intensive for cooling compared to the cask, which is a negligible difference suggesting almost equivalent performance in this aspect. However, when compared to the cube, the sphere is 19.67% more efficient in cooling energy consumption. This substantial reduction in energy usage underscores the sphere's superior thermal performance due to its lower surface area-to-volume ratio, which minimizes heat exchange with the external environment. For heating, the sphere demonstrates further advantages. It is 16.17% more efficient than the cask and 17.57% more efficient than the cube in energy consumption for heating. These percentages reflect the sphere's inherent geometric benefit, which leads to significantly lower energy requirements to maintain interior comfort conditions during colder periods. In terms of environmental impacts, The sphere's advantage is pronounced when examining the percentage increases in impacts caused by the cube and cask geometries. The cube, notably, results in substantially higher environmental impacts across all categories when compared to the sphere, with a marked increase in fossil fuel consumption (76.32%), GWP (76.32%), ecotoxicity (76.32%), and smog formation (75.54%). Meanwhile, the cask presents higher impacts than the sphere by 26.48% for both fossil fuel and GWP, 26.48% for ecotoxicity, and 17.72% for smog potential. consequently, In the assessment of environmental impacts associated with geometric configurations, the sphere emerges as the most sustainable design, demonstrating lower impact values across various categories when compared to the cask and cube. The sphere's mean values indicate a reduction in fossil fuel consumption, global warming potential (GWP), ecotoxicity, and smog formation, underscoring its environmental efficiency.

This analysis accentuates the sphere's lower ecological footprint, promoting it as a preferable option in environmental impact minimization. The results suggest that the sphere's geometry, with its reduced surface area to volume ratio, contributes to lessened energy consumption and subsequent environmental effects. Therefore, in the context of sustainable design and construction, the sphere is recommended over the cask and cube geometries for reducing environmental impacts, advancing ecological conservation, and supporting public health initiatives.

4.1.6 Sensitivity Analysis (Step5)

At this juncture in the study, it was crucial to conduct a sensitivity analysis of the output data, specifically regarding environmental impact categories, by examining the influence of input data, including variables such as 'Radius' and 'Height'. This analysis was aimed at discerning which variables exert a more significant effect on the outputs, or in other words, determining the sensitivity of the outputs to variations in these variables. Such an analysis assists designers in selecting appropriate dimensions during the design stage. For this purpose, Python was identified as a suitable software tool, capable of analysing the data through the application of diverse algorithms.

4.1.6.1 Sensitivity Analysis of Sphere Outputs

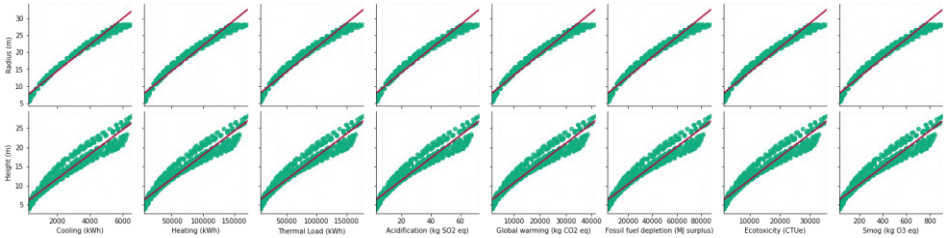
Table 4.5 presents the input and output data for the Sphere model. The inputs comprise radius and height, while the output encompasses all environmental impact categories caused by variations in sphere areas and volumes, as applied to the prototype model.

in:Radius	in:Height	out:Thermal Load (kWh)	out:Area (m2)	Acidification	Carcinogenics	Ecotoxicity	Eutrophication	Fossil fuel depletion	Global warming	Non carcinogenics	Ozone depletion	Respiratory effects	Smog
5.65	0.7	6234.639	100.2875	2.565759	1.11E-05	1251.15	0.83517	3102.577	1454.17	4.90E-05	0.000182	0.30846	31.886
5.65	0.7	6234.639	100.2875	2.565759	1.11E-05	1251.15	0.83517	3102.577	1454.17	4.90E-05	0.000182	0.30846	31.886
5.65	0.71	6264.742	100.2875	2.578148	1.11E-05	1257.19	0.83921	3117.558	1461.19	4.92E-05	0.000183	0.30995	32.04
5.65	0.73	6340.585	100.2875	2.609359	1.13E-05	1272.41	0.84937	3155.3	1478.88	4.98E-05	0.000185	0.3137	32.428
5.65	0.75	6402.696	100.2875	2.63492	1.14E-05	1284.87	0.85769	3186.208	1493.37	5.03E-05	0.000187	0.31678	32.745
5.65	0.77	6465.597	100.2875	2.660806	1.15E-05	1297.5	0.86611	3217.51	1508.04	5.08E-05	0.000188	0.31989	33.067
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
27.87	0.93	167183.2	2440.191	68.80138	0.0002969	33549.8	22.3954	83196.27	38993.9	0.001313	0.004873	8.27144	855.02
27.34	1	167549.3	2348.264	68.95205	0.0002976	33623.3	22.4444	83378.47	39079.3	0.001316	0.004883	8.28956	856.89
27.87	0.94	167964.8	2440.191	69.12303	0.0002983	33706.7	22.5001	83585.21	39176.2	0.001319	0.004895	8.31011	859.02
28.21	0.93	171251.8	2500.092	70.47575	0.0003041	34366.3	22.9404	85220.95	39942.8	0.001345	0.004991	8.47274	875.83
28.21	0.93	171251.8	2500.092	70.47575	0.0003041	34366.3	22.9404	85220.95	39942.8	0.001345	0.004991	8.47274	875.83
27.76	1	171872.2	2420.967	70.73108	0.0003052	34490.8	23.0235	85529.71	40087.6	0.00135	0.005009	8.50344	879
28.21	0.94	172051.7	2500.092	70.80493	0.0003055	34526.8	23.0475	85619.01	40129.4	0.001351	0.005014	8.51232	879.92
27.87	1	173223.7	2440.191	71.28725	0.0003076	34762	23.2045	86202.24	40402.8	0.00136	0.005049	8.5703	885.91
28.21	1	177435.8	2500.092	73.02067	0.0003151	35607.3	23.7688	88298.33	41385.2	0.001393	0.005171	8.7787	907.46

Table 4-13: Input and output data's Sphere, Appendix D, Page 457

Diagram 4.4 is a scatter plot with fitted lines. This type of diagram is commonly known as a scatter plot matrix or a pairs plot. It is a statistical way to analyze the relationship between different variables, "radius" and "height". Each plot in the matrix shows the relationship between two variables. The diagonal could potentially show a histogram or a kernel density estimate for each variable. The plots below the diagonal mirror the ones above, showing the same relationships. The scatter plots with fitted lines indicate regression analysis, with the red line representing the best-fit line through the data points, which are shown in green. The best-fit line is typically the result of a linear regression model that minimizes the sum of squared differences between the observed values (the green points) and the values predicted by the model (the red line). These elements elucidate the character of the interdependence between the variables under consideration—namely, whether the correlation is positive or negative—and the robustness of this relationship, as indicated by the proximity of the data points to the line of best fit. A dense aggregation of data points around the regression line would imply a substantial linear correlation between the variables. The visual evidence provided by the scatter plot matrix strongly suggests that there is a significant association between the variable denoted as 'radius' and the various output categories presented.

Diagram4-11 : Sphere Scotter plot, Appendix C, Page 402



One of the primary objectives of this scholarly inquiry is to deduce a mathematical correlation—akin to a formula—between the input parameters (radius and height) and the resultant outputs (cooling, heating, and environmental categories). Such a formulation has the potential to significantly expedite the predictive processes for researchers and designers, enabling the anticipation of output quantities without the prerequisite of comprehensive project modeling. This advancement stands to contribute to substantial time efficiency gains. However, it is imperative to acknowledge that the applicability of this formula is contingent upon identical environmental conditions, with the climatic context of Boston serving as a paradigmatic case study. Moreover, the deliberate exclusion of variables is designed to minimize extraneous variability. The subsequent equation elucidates the mathematical interplay between radius and height as correlating with the output data.

- **Cooling (kWh)** = -1559.5485561731143 + (199.230575647067 58 * Radius (m)) + (60.22177990295571 * Height (m))
- **Heating (kWh)** = -43023.57320863452 + (4588.725527101116 * Radius (m)) + (2258.0705300703266 * Height (m))
- **Thermal Load (kWh)** = -44583.12176599825 + (4787.956102602325 * Radius (m)) + (2318.292310349433 * Height (m))
- **Acidification (kg SO2 eq)** = -18.347423197902575 + (1.970401653924413 * Radius (m)) + (0.9540536515090732 * Height (m))
- **Global warming (kg CO2 eq)** = -10398.589407164518 + (1116.7452533377416 * Radius (m)) + (540.7196469172408 * Height (m))
- **Fossil fuel depletion (MJ surplus)** = -22186.141737884143 + (2382.6566763639557 * Radius (m)) + (1153.6644305412458 * Height (m))
- **Ecotoxicity (CTUe)** = -8946.811763611993 + (960.8331647506765 * Radius (m)) + (465.2281871367997 * Height (m))
- **Smog (kg O3 eq)** = -228.0104133787122 + (24.486931532694705 * Radius (m)) + (11.856387957022969 * Height (m))

Subsequently, the precision of the formulated equations was rigorously evaluated utilizing the Python programming language as a computational tool. The outcomes of this analytical procedure have demonstrated a commendably high degree of accuracy, quantified at 96% across all derived formulas. This empirical evidence substantiates the pragmatic utility of the equations within the specified domain of application (Diagram 4.5)

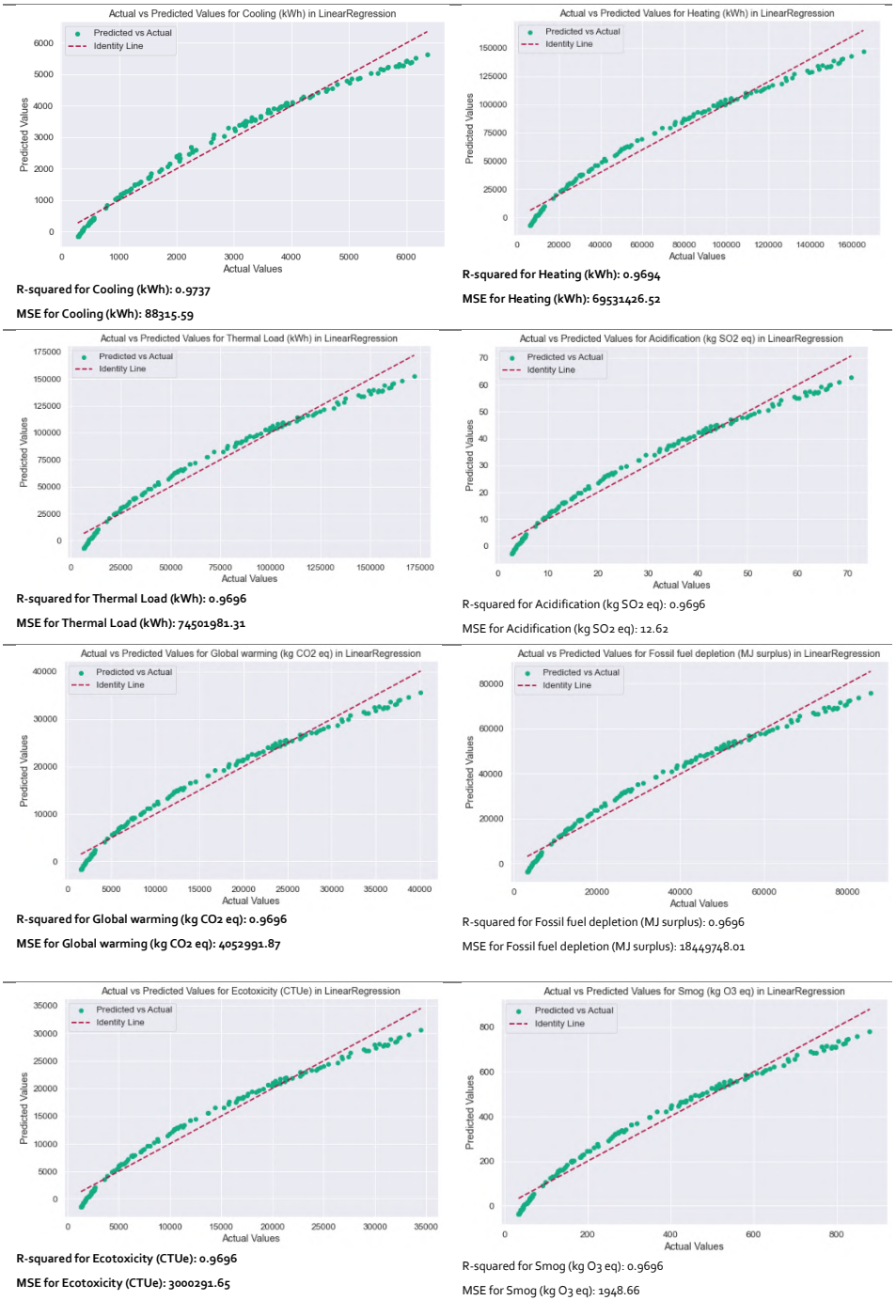


Diagram 4-14: Actual vs Predicted values for different outputs, Appendix C, Page 403

In the ensuing stage of analytical rigor, an evaluative comparison was conducted between the variables of radius and height, employing a model scoring metric to determine their respective sensitivities and consequent influences on the resultant outputs. This analytical dichotomy provides critical insights that are instrumental in informing the decision-making paradigms integral to the design phase, thereby enabling the judicious selection of dimensions that are attuned to environmental considerations. For the purposes of this assessment, a random sample of 20 data points was selected for analysis. The resultant data delineate a more conspicuous prominence in the model scores attributed to the radius variable in comparison to height. Moreover,

the analysis infers that modifications to the radius are imbued with a more significant propensity to influence the aggregate output data, as opposed to alterations in height (Diagram 4.6).

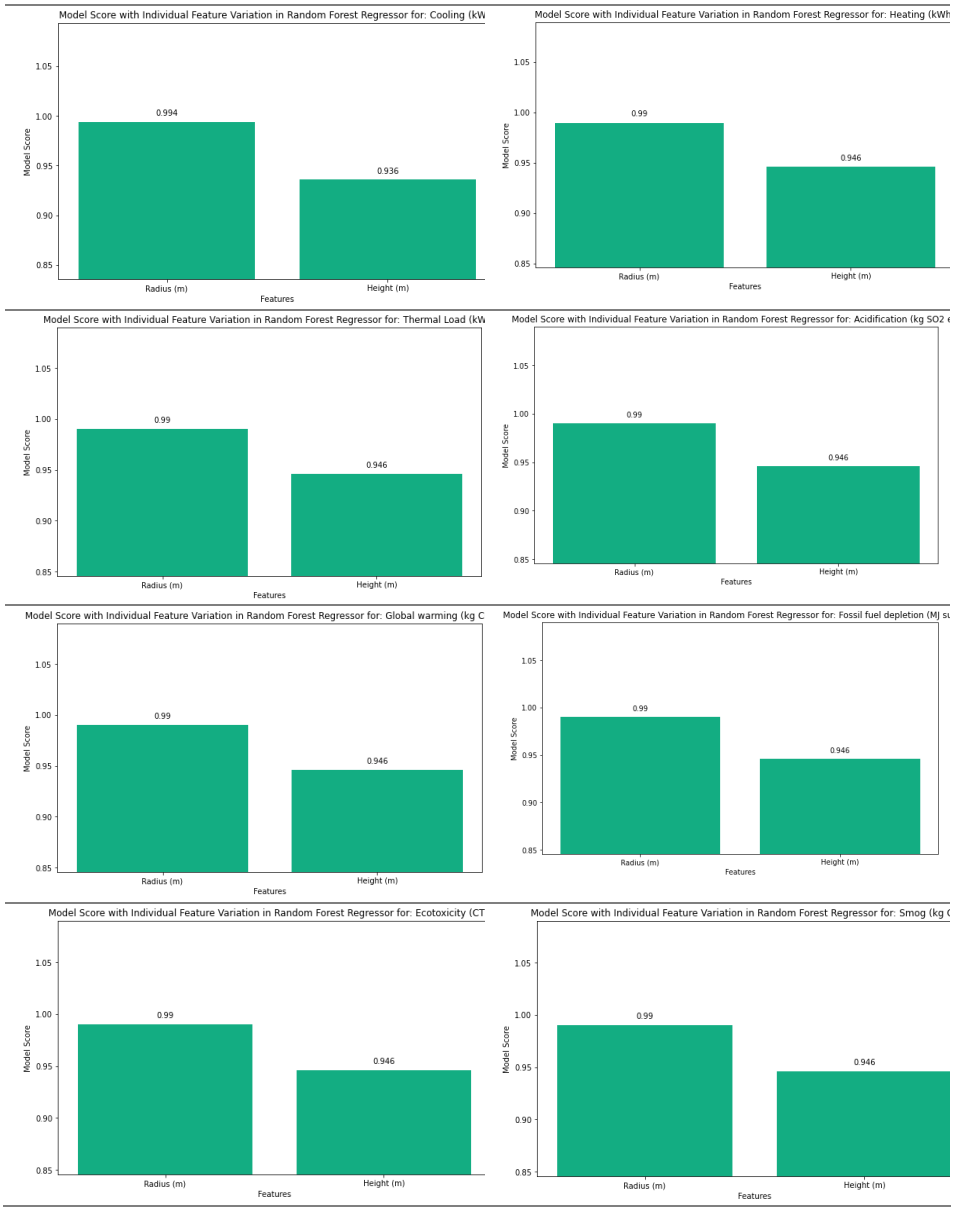


Diagram 4-17:Model Score with individual Features in Random Data (Sphere), Appendix C, Page 405

To appraise the outcomes of the preceding analytical stage, an examination delineating the differential sensitivities of radius versus height was executed utilizing advanced statistical methodologies, namely Feature Importance in Random Forest (FRF) and Extreme Gradient Boosting (XGBoost). The empirical findings from this inquiry underscore the pre-eminences of the radius parameter in addressing issues pertinent to environmental impact (Diagram4.7).

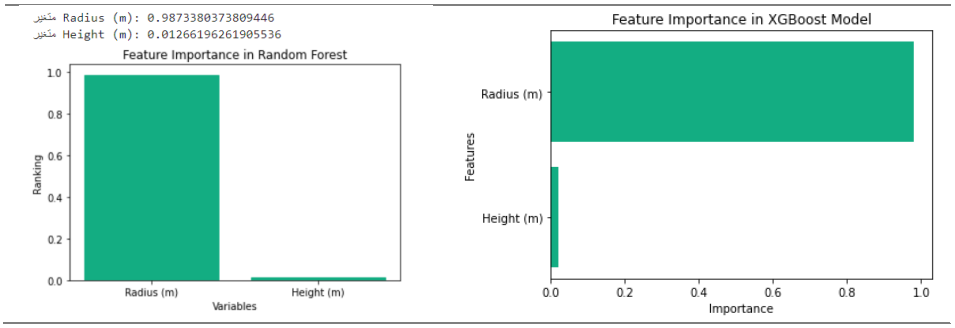
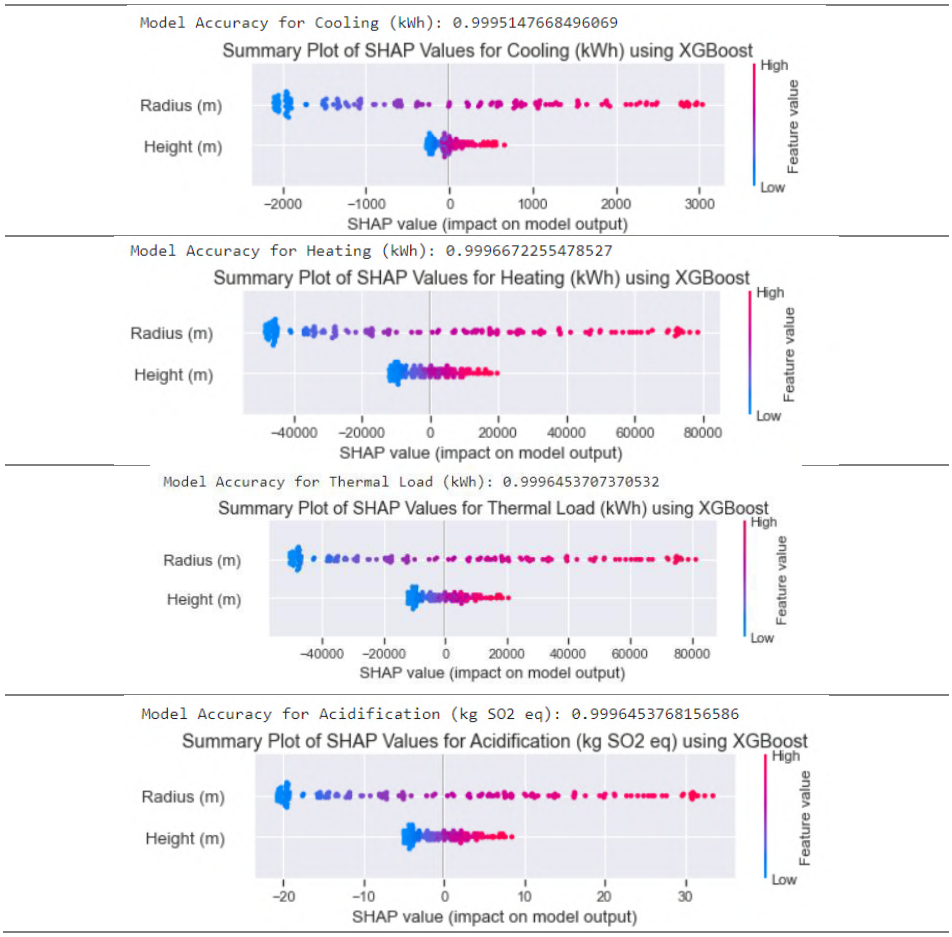


Diagram 4-20: FRF & XGBoost (Sphere), Appendix C, Page 408

The series of SHAP summary plots for different environmental and energy consumption metrics using XGBoost demonstrate the varying degrees of feature importance between 'Radius (m)' and 'Height (m)'. Across the outputs for cooling, heating, thermal load, acidification, global warming, fossil fuel depletion, ecotoxicity, and smog, the radius typically shows a wider spread of SHAP values, indicating a more significant and variable impact on the model output. Height tends to have a more unidirectional impact, particularly for energy consumption metrics. The colour gradient from blue to pink signifies the low to high feature values, respectively, correlating with their impact on the model's prediction. This analysis reveals the intricate relationship between geometric factors and their environmental implications, with radius consistently appearing as a strong predictor across multiple impact categories (Diagram 4.8).



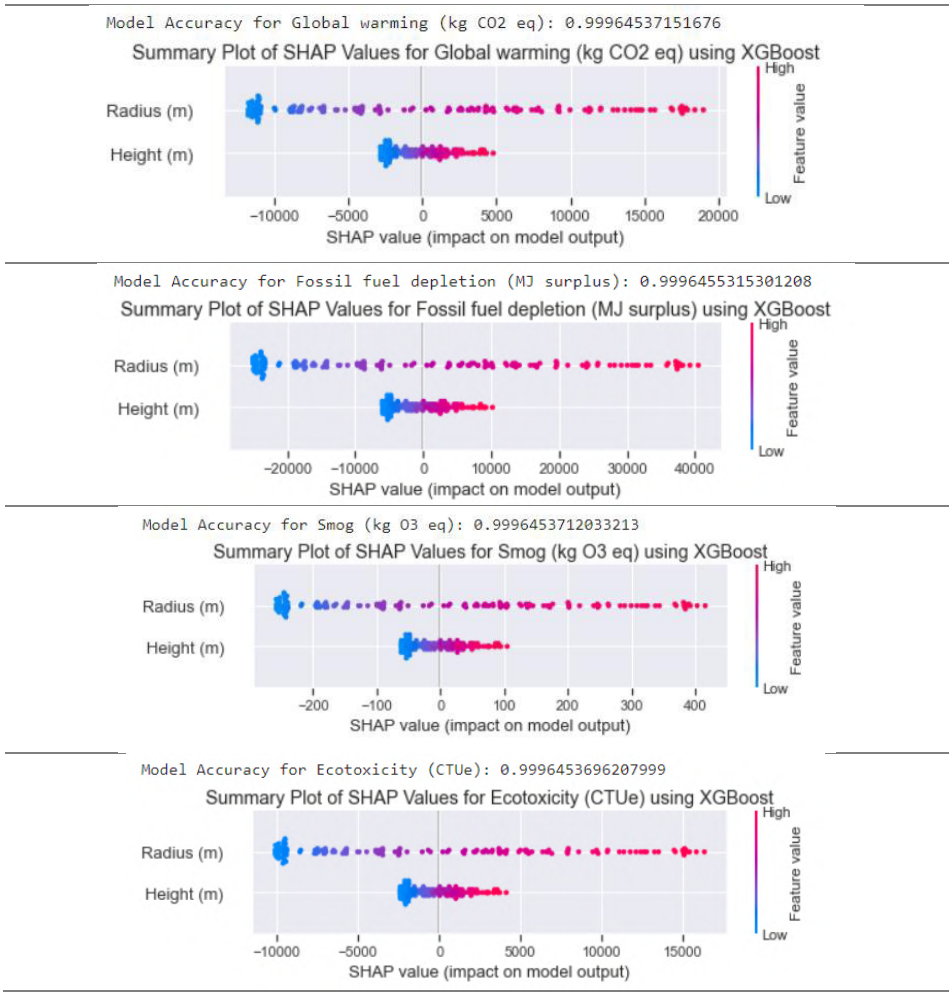


Diagram 4-23: SHAP diagram (Sphere), Appendix C, Page 408

A Pearson correlation heatmap is employed to visually discern the degree to which two variables are linearly related (Diagram 4.9). The heatmap uses a spectrum of colors to convey the strength of this relationship; typically, a shade of red signifies a strong positive correlation (near +1), indicating that an increase in one variable corresponds with an increase in another. A shade of blue denotes a strong negative correlation (near -1), representing an inverse relationship. A neutral color, often white or light yellow, illustrates a negligible correlation (around 0).

The provided heatmap diagram elucidates the relationship between the spherical dimension of radius, referred to as 'radius', and various environmental impact parameters. The color intensities in the diagram vividly display the sensitivity of these environmental metrics to changes in the radius of a sphere.

A preliminary analysis of the heatmap reveals a preponderance of deep red cells along the row corresponding to the radius, signifying a strong positive correlation between the radius of a sphere and each of the environmental impacts listed, including cooling (kWh), heating (kWh), thermal load (kWh), acidification (kg SO_2 eq), global warming (kg CO_2 eq), fossil fuel depletion (MJ surplus), ecotoxicity (CTUe), and smog (kg O_3 eq). The uniformity of the red shade indicates that the radius exhibits a consistently strong linear relationship with these environmental factors.

This observation implies that the radius is a critical variable in environmental impact studies concerning spherical structures or objects. For instance, in spheres utilized in

architectural designs or industrial applications, the radius's influence on energy consumption (cooling and heating), environmental pollution (acidification, smog), and resource depletion (fossil fuel) is remarkably significant. The high sensitivity to radius alterations mandates careful consideration of dimensionality in the design phase to mitigate adverse environmental impacts.

Given the sphere's central role in various scientific and engineering applications, understanding the implications of its radius on environmental factors is indispensable. The heatmap not only confirms the pronounced impact of the radius on environmental outcomes but also underscores the necessity for multidisciplinary approaches in design and evaluation to harmonize industrial and architectural endeavors with ecological sustainability.

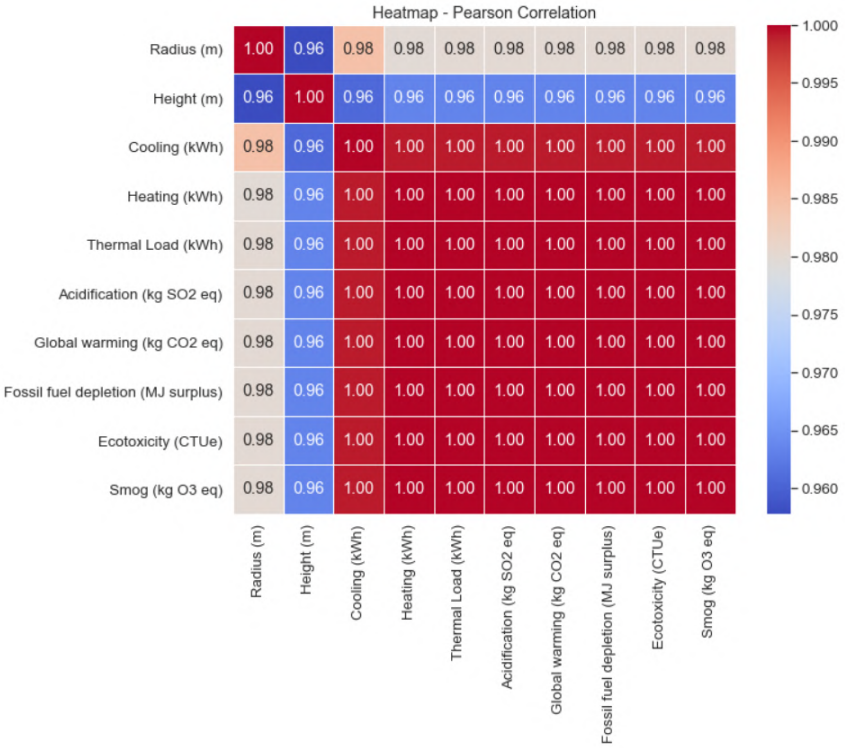


Diagram 4-26: Heatmap-Pearson Correlation, Appendix C, Page 410

A Spearman correlation heatmap, is an advanced statistical tool used for the discernment of monotonic relationships between variables. Unlike Pearson correlation, which measures linear relationships, the Spearman correlation coefficient is designed to identify both linear and non-linear monotonic relationships. In this context, monotonic relationships imply that as one variable increases or decreases, the other variable will consistently increase or decrease, though not necessarily at a constant rate.

The heatmap employs a chromatic scale to represent Spearman correlation coefficients, where values approaching +1 are color-coded in deeper shades, indicating a strong positive monotonic association. In the heatmap presented, the preeminent deep shades uniformly color all the cells pertaining to the radius variable, reflective of Spearman correlation coefficients that are remarkably close to +1. This uniformity underscores a potent and consistent monotonic relationship between the radius of a sphere and a suite of environmental impact factors, which include—but are not limited to—cooling (kWh), heating (kWh), thermal load (kWh), acidification (kg SO_2 eq), global

warming (kg CO_2 eq), fossil fuel depletion (MJ surplus), ecotoxicity (CTUe), and smog (kg O_3 eq) (Diagram 4.10).

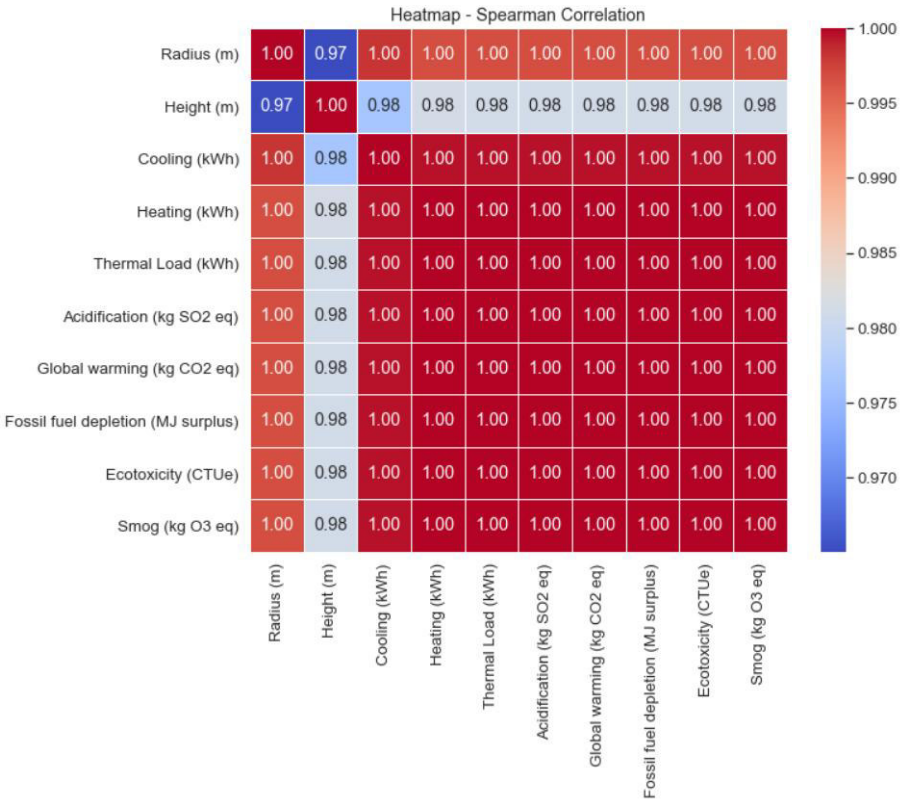


Diagram 4-29: Spearman Correlation (Sphere), Appendix C, Page 411

This analysis reveals that variations in the radius exhibit a pervasive and marked influence on these environmental parameters. It is particularly noteworthy that the strength of this relationship is remarkably robust across the spectrum of environmental impacts examined, with correlation coefficients uniformly registering at or above 0.97. This suggests that any modification in the radius of a sphere is almost certain to have a corresponding and significant effect on these environmental measures. The academic implications of such findings are profound. They point to the radius as a critical factor in the environmental impact assessments of spherical structures. When considering the ecological footprint of spheres in various applications—be it in industrial design, architecture, or environmental policy—the radius emerges as a pivotal element whose modification could have far-reaching effects on sustainability metrics.

As such, the heatmap transcends its function as a mere statistical instrument and emerges as a critical component in the decision-making arsenal for designers and environmental scientists. It facilitates a deeper understanding of the environmental implications inherent in the geometric properties of spheres, thus guiding the path toward more ecologically responsive and responsible design paradigms.

In the final analysis, an investigation into the relative significance of each feature with respect to the specified objectives was conducted. The results of this investigation reveal that the variable 'radius' exerts a more substantial influence on all output measures in comparison to 'height'(Diagram 4.11).

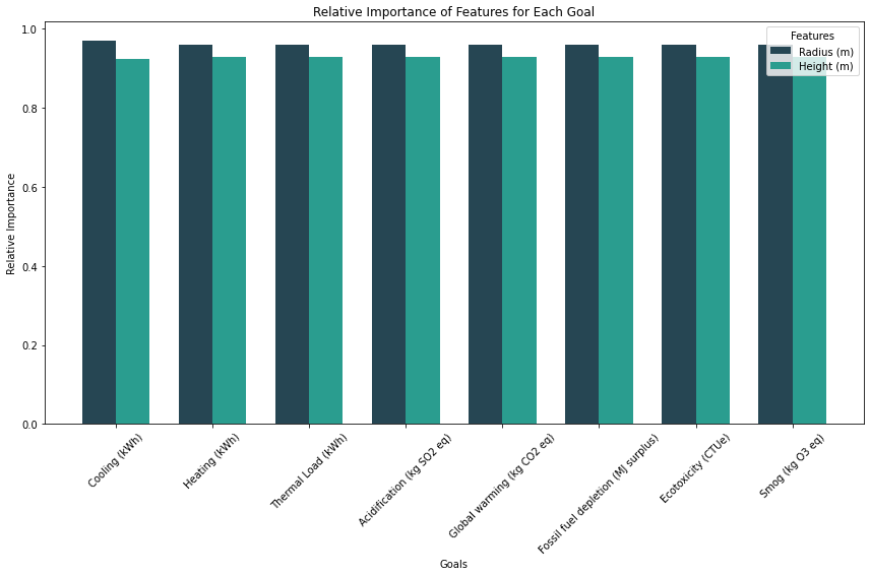


Diagram 4-32: Relative Importance of features for each goal (Sphere), Appendix C Page 411

4.1.6.2 Sensitivity Analysis of Cask outputs

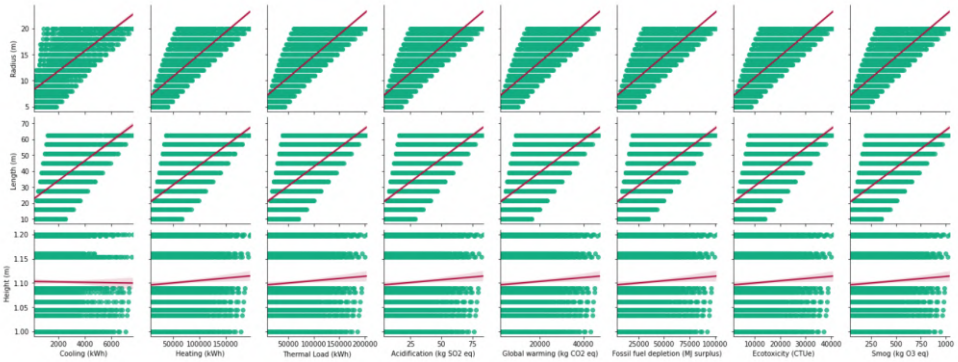
Table 4.6 delineates the input and output parameters for the Cask model. The inputs include radius, height, and length, whereas the output encapsulates all environmental impact categories resulting from alterations in cask surface areas and volumes, as implemented in the prototype model.

in:Radius	in:Lenght (Y)	in:Height (Z)	out:Thermal Load (kWh)	out:Area (m2)	Acidification	Carcinogenics	Ecotoxicity	Eutrophication	Fossil fuel depletion	Global warming	Non carcinogenics	Ozone depletion	Respiratory effects	Smog
5	10	1	8264.1484	100	3.40096929	1.47E-05	1658.4254	1.10704	4112.533	1927.53	6.49E-05	0.000241	0.4088716	42.2651
5	10	1.045	8329.7032	100	3.42794725	1.48E-05	1671.5807	1.11582	4145.156	1942.82	6.54E-05	0.000243	0.4121149	42.6004
5	10	1.061	8412.5221	100	3.46202995	1.49E-05	1688.2006	1.12692	4186.369	1962.14	6.61E-05	0.000245	0.4162124	43.024
5	10	1.033	8417.1299	100	3.46392623	1.49E-05	1689.1253	1.12753	4188.662	1963.22	6.61E-05	0.000245	0.4164404	43.0475
5	10	1.081	8504.6934	100	3.49996149	1.51E-05	1706.6972	1.13926	4232.237	1983.64	6.68E-05	0.000248	0.4207726	43.4954
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
20	62.497	1.061	191092.97	2499.88	78.6410517	0.000339361	38347.984	25.5982	95094.64	44570.6	0.001501	0.005569	9.4543901	977.302
19	62.497	1.2	191912.06	2374.89	78.9781362	0.000340816	38512.357	25.708	95502.25	44761.7	0.001507	0.005593	9.4949151	981.491
20	62.497	1.081	192984.8	2499.88	79.4196019	0.000342721	38727.631	25.8517	96036.08	45011.9	0.001515	0.005625	9.5479891	986.978
20	62.497	1.089	193339.38	2499.88	79.5655248	0.000343351	38798.787	25.8992	96212.53	45094.6	0.001518	0.005635	9.5655322	988.791
20	62.497	1.16	195020.92	2499.88	80.2575339	0.000346337	39136.234	26.1244	97049.32	45486.8	0.001531	0.005684	9.648727	997.391
20	62.497	1.197	198929.21	2499.88	81.8659245	0.000353278	39920.539	26.648	98994.23	46398.3	0.001562	0.005798	9.842091	1017.38
20	62.497	1.154	199803.82	2499.88	82.2258542	0.000354831	40096.052	26.7651	99429.46	46602.3	0.001569	0.005823	9.8853625	1021.85
20	62.497	1.2	203630.45	2499.88	83.800638	0.000361626	40863.969	27.2777	101333.7	47494.9	0.001599	0.005935	10.074686	1041.42

Table 4-16: Input and output data's Cask, Appendix D, Page 457

Diagram 4.12 shows the scatter plot of Cask, The scatter plots show a clear, positive trend indicating that as the radius increases, the environmental impacts also increase. The trend lines on the scatter plots are steep and the data points are closely clustered around these lines, which reinforces the conclusion from the statistical analysis. Outputs such as "Carcinogenic," "Non-carcinogenic," "Ozone depletion," "Fossil fuel depletion," "Respiratory effects," "Smog," "Thermal Load (kWh)," and "Global warming" are all significantly impacted by the radius, as indicated by the strong upward trends in the scatter plots. This is in line with the high correlation coefficients, indicating these outputs are highly sensitive to changes in the radius. Among the three input variables, "Radius" seems to have the strongest effect on the outputs, followed by "Length," with "Height" having the least effect.

Diagram 4-35: Scatter plots (Cask), Appendix C, Page 412



This is visually apparent in the scatter plots and is supported by the calculated correlation coefficients. Considering the visual trends in the scatter plots, it appears that all outputs are more sensitive to changes in "Radius" than to changes in "Length" or "Height." In conclusion, the scatter plot diagrams corroborate the statistical analysis, with "Radius" being the most influential variable on the environmental impacts, and these impacts are quite sensitive to changes in the cask's radius. This indicates that in the design and evaluation of the cask model, particular attention should be paid to the radius as a critical factor influencing environmental performance.

one of on important aims of this academic investigation is to establish a mathematical relationship — in the form of a precise formula — between the input parameters (length, radius, and height) for a cask and the corresponding outputs, which include cooling, heating, and various environmental impact categories. It is crucial to recognize, however, that the utility of this formula is dependent on uniform environmental conditions, using the climate specifics of Boston as a representative example for our analysis. Furthermore, the intentional omission of certain variables aims to reduce the influence of external factors on variability. The derived formulas on the following will reveal the quantitative connections between the cask's length, radius, and height and their combined effects on the observed outputs.

Cooling (kWh) = -2390.3853293583074 + (228.855490779794 * Radius (m)) + (53.98660418947621 * Length (m)) + (-29.526787523852388 * Height (m))

Heating (kWh) = -107779.46480580332 + (6752.440080761253 * Radius (m)) + (1464.699352759685 * Length (m)) + (37351.673842455035 * Height (m))

Thermal Load (kWh) = -110169.85012833374 + (6981.295571425365 * Radius (m)) + (1518.685956936693 * Length (m)) + (37322.14705022736 * Height (m))

Acidification (kg SO_2 eq) = -45.3385223824580 95 + (2.873033095070761 * Radius (m)) + (0.6249892975810843 * Length (m)) + (15.3592929248626 17 * Height (m))

Global warming (kg CO_2 eq) = -25696.07042242102 + (1628.3208375779004 * Radius (m)) + (354.2190649487787 * Length (m)) + (8705.036067923265 * Height (m))

Fossil fuel depletion (MJ surplus) = -54824.42263483919 + (3474.1401437237982 * Radius (m)) + (755.7519653308531 * Length (m)) + (18572.823336499307 * Height (m))

Ecotoxicity (CTUe) = -22108.566473150182 + (1400.9861775118686 * Radius (m)) + (304.7654997397117 * Length (m)) + (7489.700385624711 * Height (m))

Smog (kg O_3 eq) = -563.4390790774015 + (35.7042761050016 * Radius (m)) + (7.766979949223844 * Length (m)) + (190.875780800755 14 * Height (m))

The accuracy of the developed equations was thoroughly assessed using Python as the computational instrument. The results of this analytical process have exhibited an impressively high level of precision, measured to be 95% for all the equations formulated (Diagram 4.13).

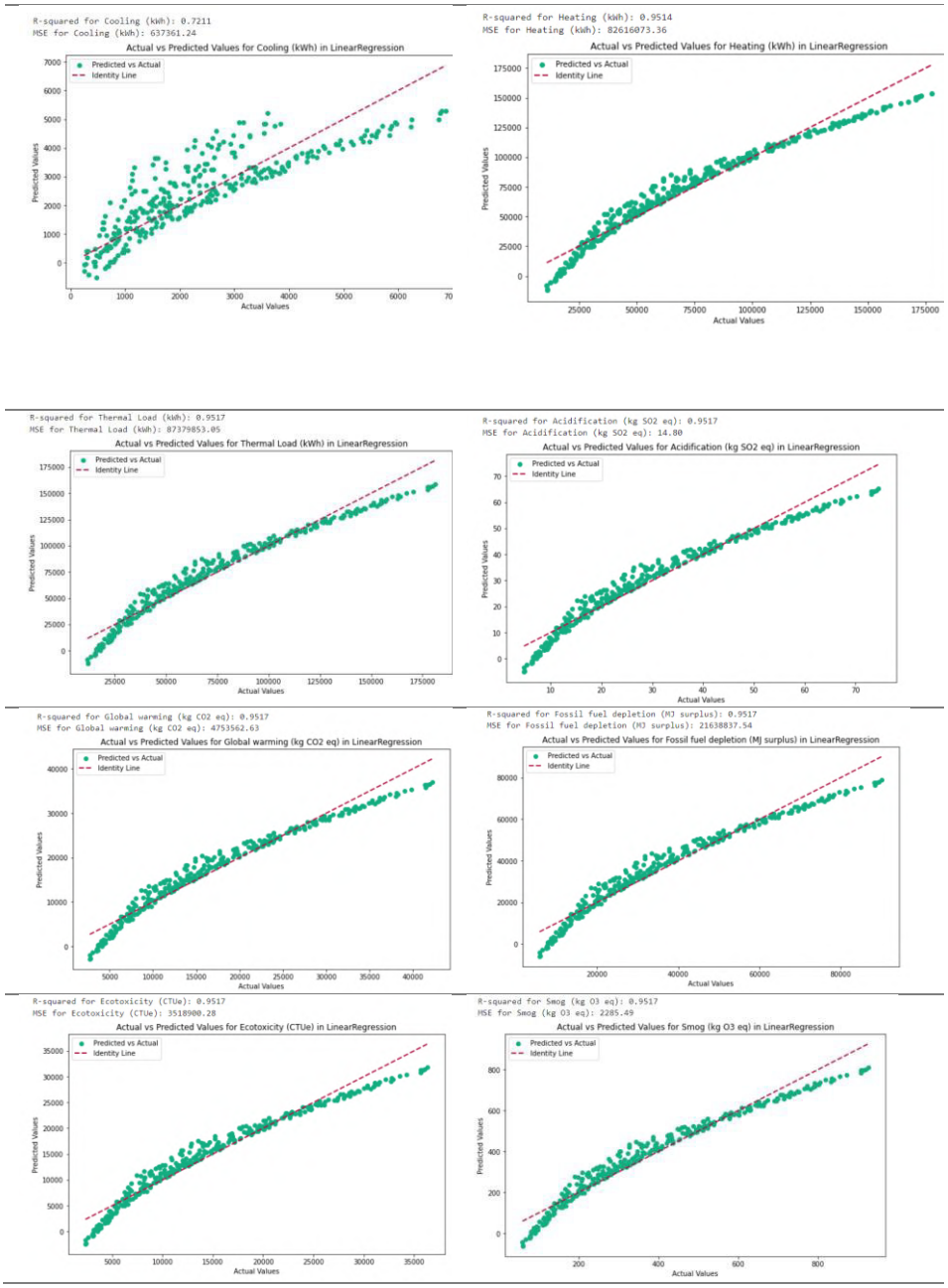


Diagram 4-38: Actual values vs predicted values (Cask), Appendix C, Page 412

The evaluation of variables—specifically radius, height, and length—involved the application of a model evaluation metric to determine their individual sensitivities and the resultant impact on the output metrics. This analytical comparison yields essential insights that are critical in guiding the decision-making framework essential to the design process. It empowers the strategic selection of dimensions that are in harmony with ecological considerations. For the analysis, a carefully chosen random subset of 20

data points was examined. The findings highlight a notably stronger influence of the radius variable in the model scores when compared to height and length. Additionally, the analysis indicates that variations in the radius hold more substantial potential to alter the collective output data, much more so than changes in height or length (Diagram 4.14).

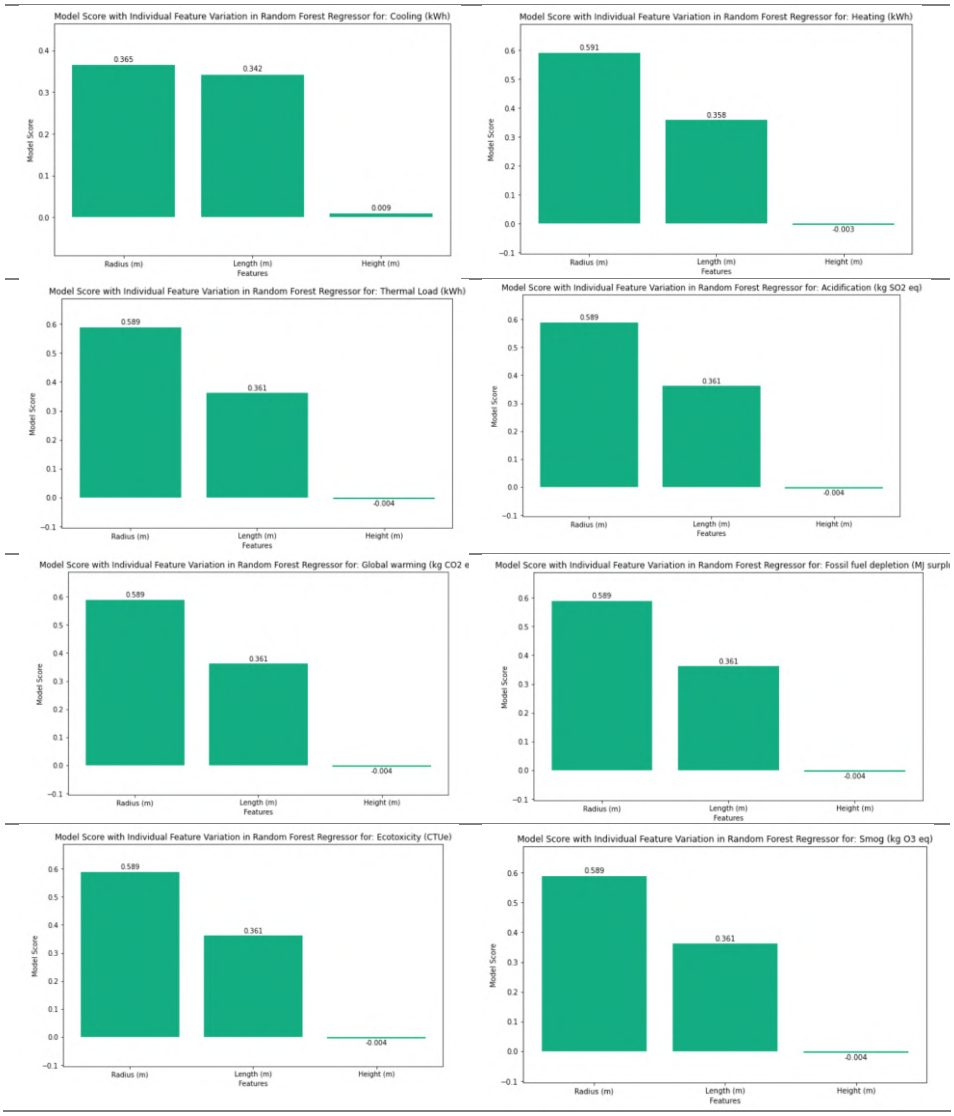


Diagram 4-41: Model Score with individual Features in Random Data (Cask), Appendix C, Page 415

To evaluate the results from the previous stage of analysis, a detailed investigation into the distinct sensitivities of radius compared to height was carried out using sophisticated statistical techniques, specifically Feature Importance in Random Forest (FRF) and Extreme Gradient Boosting (XGBoost). The concrete evidence gathered from this study highlights the dominance of the radius parameter when considering factors relevant to environmental impact (Diagram 4.15).

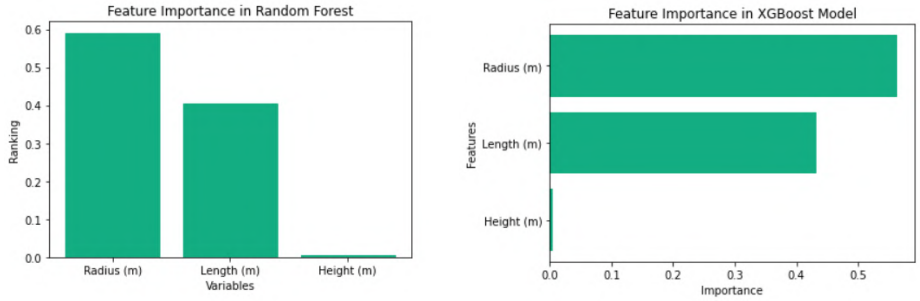
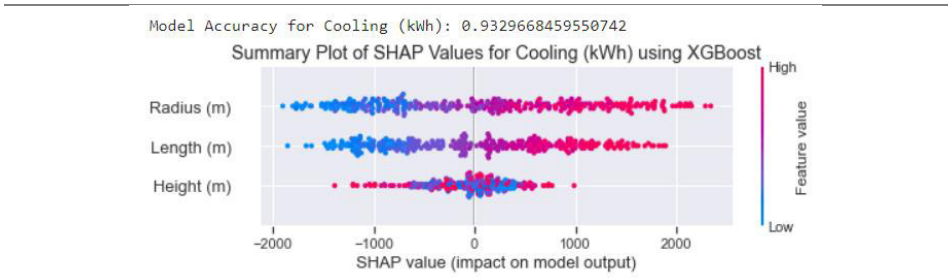
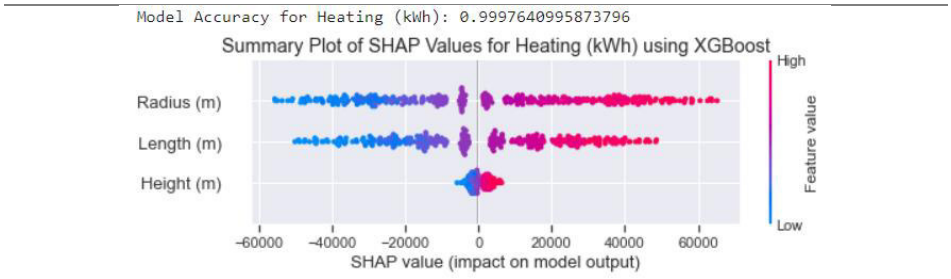


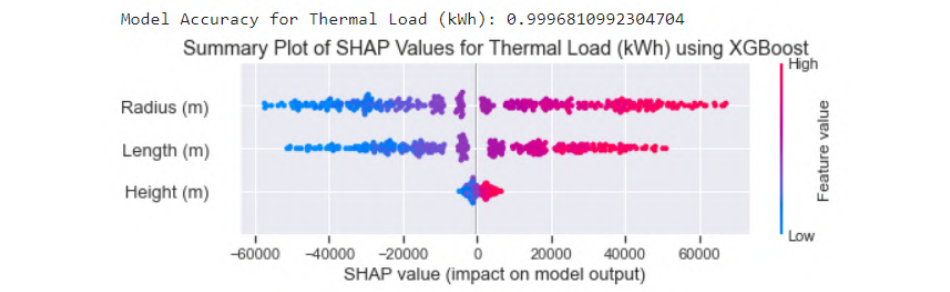
Diagram 4-44: FRF & XGBoost (Cask), Appendix C, Page 417

The SHAP summary plots for the cask model, utilizing XGBoost for a range of environmental and energy-related outputs, elucidate the differential feature significance among 'Radius (m)', 'Length (m)', and 'Height (m)'. The SHAP values for radius generally display a broader distribution across the model predictions for cooling, heating, thermal load, acidification, global warming, and fossil fuel depletion, which signifies its substantial and varied influence on the predicted outcomes. Length also presents a notable spread of SHAP values, although not as prominently as radius, suggesting a considerable effect on the model's predictions. In contrast, height shows

a narrower range of SHAP values, indicating a more consistent yet lesser impact, especially apparent in the energy consumption outputs. The color gradient present in these plots, ranging from blue to pink, denotes the progression from low to high values of each feature and their corresponding influence on the model's predictions. This analytical perspective underscores the complex interplay between the cask's dimensional attributes and their consequential environmental and energy impacts. Notably, the radius emerges as a consistently pivotal factor, influencing a diverse array of impact categories within the cask model's predictive framework (Diagram 4.16).







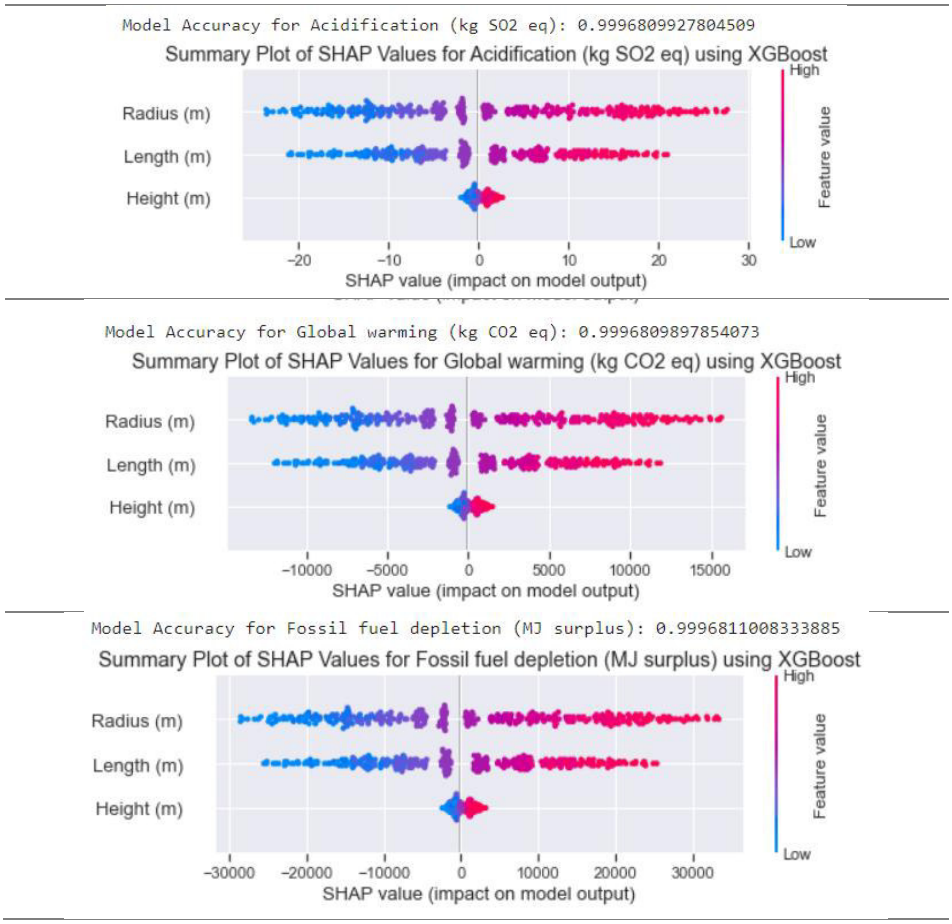


Diagram 4-47: SHAP Diagram (Cask), Appendix C, Page417

diagram 4.17 heatmap generated from a Pearson correlation analysis. This type of analysis is used to determine the degree of linear correlation between variables, with a range of +1 to -1. A value of +1 indicates a perfect positive linear relationship, -1 indicates a perfect negative linear relationship, and 0 indicates no linear relationship.

Below's a breakdown of what the heatmap indicates:

Radius (m): The radius shows a strong positive correlation of 0.76 with all environmental impacts listed. This means that changes in the radius have a strong association with changes in each of these environmental impact factors.

Length (m) and Height (m): Length has a moderate positive correlation of around 0.6 with the environmental impacts, suggesting that it has a less pronounced but still significant relationship with the outcomes compared to radius. Height has a negligible correlation with most environmental impacts, indicating little to no linear relationship with these factors.

Environmental Goals: All the environmental impact factors such as cooling, heating, thermal load, acidification, global warming, fossil fuel depletion, ecotoxicity, and smog have very high correlations with each other (0.9 to 1.00). This suggests that within the model, these impacts tend to increase or decrease together; if one impact is high, the others are likely to be high as well.

It is important to note that correlation does not imply causation. High correlation means that there is a relationship between the increase or decrease of the variables, but it does not indicate that one variable causes the other to change.

In summary, the heatmap provides a clear visual indication that within this dataset, the radius has the strongest association with the environmental impacts measured, while the length has a moderate association and height has little to no association. Additionally, the environmental impact factors themselves are highly interrelated, suggesting that improvements or deteriorations in one are likely to be accompanied by similar changes in the others (Diagram 4.17).

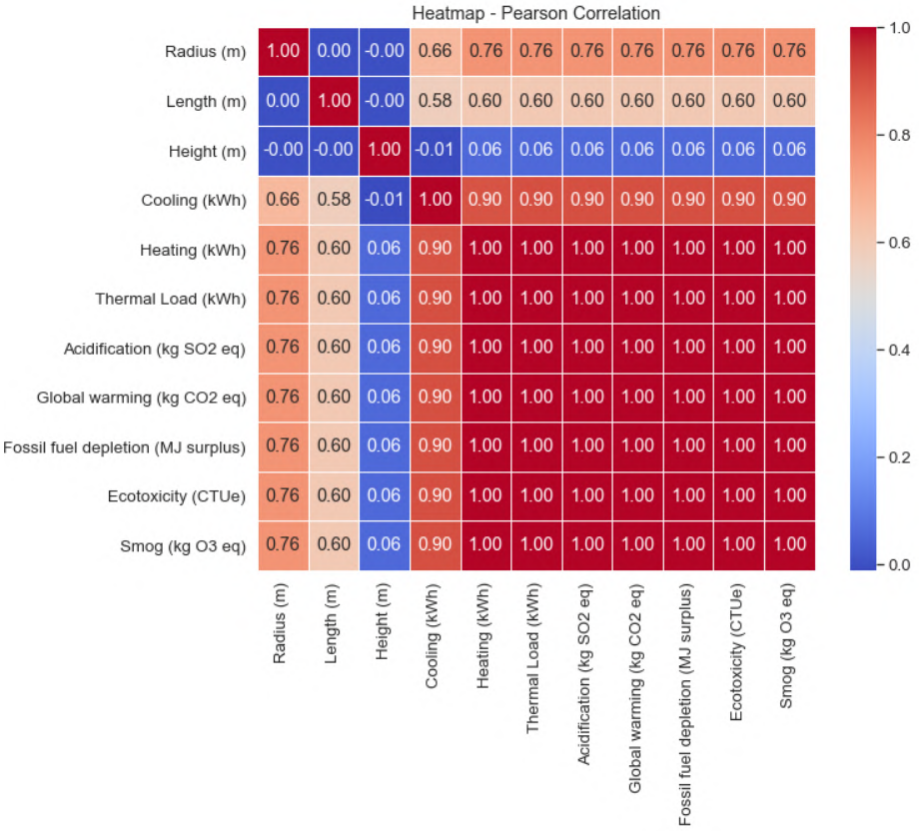


Diagram 4-50: Heatmap-Pearson Correlation (Cask), Appendix C, Page 419

Diagram 4.18 is the heatmap which is derived from a Spearman correlation analysis, which is similar to the Pearson correlation but used to detect monotonic relationships between variables, whether linear or not. A value close to +1 signifies a strong positive monotonic relationship, while a value close to -1 signifies a strong negative monotonic relationship, and a value around 0 signifies no monotonic relationship.

This heatmap demonstrates:

Radius (m): The radius demonstrates a strong positive monotonic relationship (correlations from 0.68 to 0.78) with all environmental impacts studied. Unlike the Pearson correlation, Spearman correlation captures non-linear relationships as well, reinforcing the significance of radius on environmental impacts.

Length (m): Length shows a moderate to strong positive monotonic relationship (0.59 to 0.60) with the environmental impacts, indicating its influence, although to a lesser extent than radius.

Height (m): Height has very little to no monotonic relationship with the environmental impacts, as indicated by the correlation values close to 0.

Environmental Impacts: As with the Pearson correlation heatmap, the environmental impacts categories—such as cooling, heating, thermal load, acidification, global warming, fossil fuel depletion, ecotoxicity, and smog—exhibit extremely high to

perfect monotonic correlations with one another (0.90 to 1.00). This suggests that within the context of the model, these impacts are likely to increase or decrease together in a monotonic fashion.

Overall, the Spearman correlation heatmap further supports the conclusion that the radius is the most influential variable in terms of its relationship with environmental impacts, compared to length and height. The extremely high correlations among the environmental impact factors suggest a strong interdependence in how they respond to changes within the system being studied.

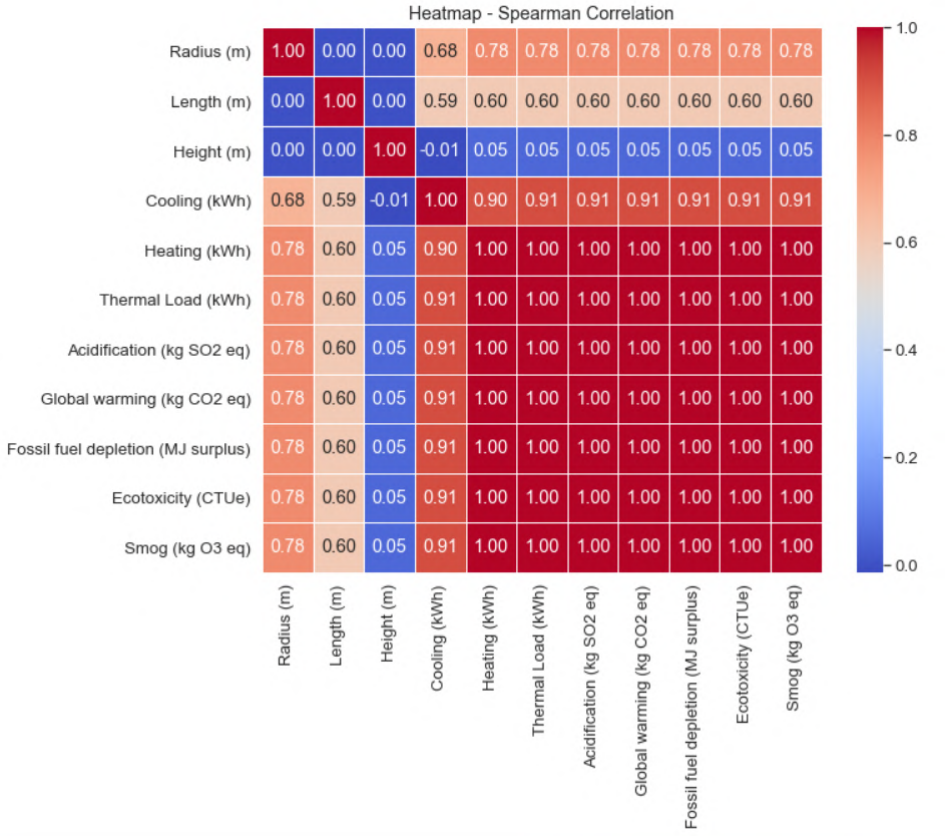


Diagram 4-53: Heatmap-spearman Correlation (Cask), Appendix C, Page 419

In conclusion, Diagram 4.19, serves as a visual representation of the sensitivity analysis conducted to evaluate the relative importance of different characteristics—namely radius, height, and length—in achieving various environmental goals. The analysis presents a hierarchy of the effects that these dimensions have on environmental impact outcomes.

Upon examining the bar chart, it is evident that the variable 'radius' consistently exerts a more substantial impact on the environmental goals compared to the variables 'height' and 'length.' This can be discerned across a range of goals, including reduction in CO_2, energy savings, and others, as indicated by the taller bars associated with the 'radius' across all goal categories. The graphical illustration effectively communicates the dominance of the 'radius' variable in influencing the environmental impacts of the tasks under consideration, thereby informing decision-makers about which dimensions to prioritize for ecological optimization.

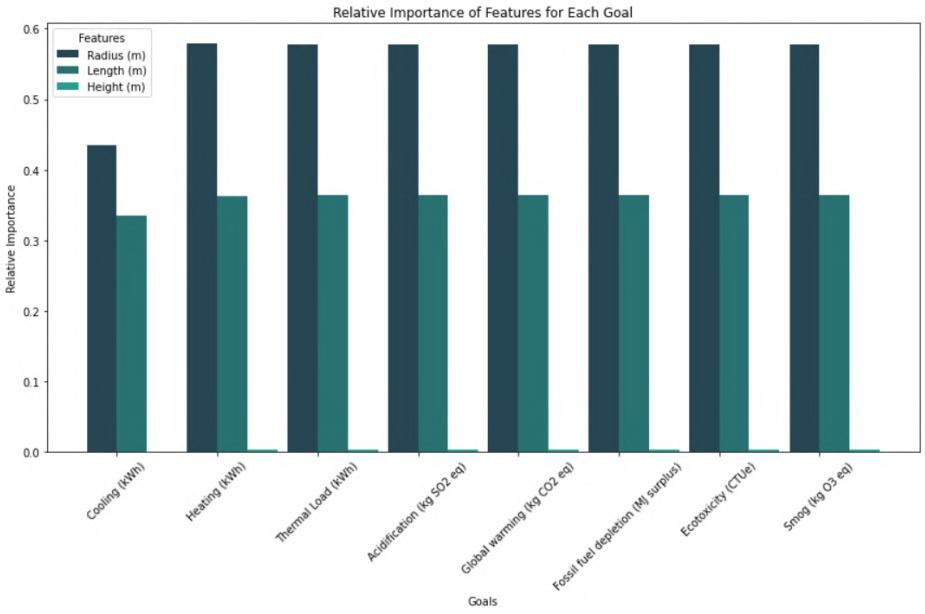


Diagram 4-56: Relative Importance of features for each goal (Cask), Appendix C, Page 420

4.1.6.3 Sensitivity Analysis of Cube Outputs

Table 4.7 delineates the input and output parameters for the Cube model. The inputs include length, width, and height, whereas the output encapsulates all environmental impact categories resulting from alterations in cube surface areas and volumes, as implemented in the prototype model.

Length (x)	Width (Y)	in:Height (Z)	out:Thermal Load (kWh)	out:Area (m2)	Acidification	Carcinogenics	Ecotoxicity	Eutrophication	Fossil fuel depletion	Global warming	Non carcinogenics	Ozone depletion	Respiratory effects	Smog
10.45	10	3.76	9010.651	104.5	3.708179568	1.60E-05	1808.231283	1.207039698	4484.019	2101.648627	7.08E-05	0.0002626	0.445805029	46.0829593
10.45	10	5.64	11218.36	104.5	4.616726637	1.99E-05	2251.268952	1.502778445	5582.656	2616.576954	8.81E-05	0.000327	0.555032439	57.3738196
14.36	10	3.76	11573.25	143.6	4.762775575	2.06E-05	2322.487255	1.550318447	5759.262	2699.351681	9.09E-05	0.0003373	0.572590745	59.1888254
16.64	10	3.76	13069.05	166.4	5.378346301	2.32E-05	2622.659947	1.750691242	6503.625	3048.232674	0.000102622	0.0003809	0.646595933	66.8387571
10.45	10	7.52	13456.05	104.5	5.537607026	2.39E-05	2700.320756	1.802531778	6696.206	3138.495316	0.00010566	0.0003922	0.665742587	68.8179508
10.45	16.99	3.76	13777.73	177.55	5.669990292	2.45E-05	2764.875225	1.845623504	6856.287	3213.524883	0.000108186	0.0004015	0.681657978	70.4631281
14.36	10	5.64	14177.87	143.6	5.834661149	2.52E-05	2845.174194	1.899225078	7055.411	3306.853772	0.000111328	0.0004132	0.701455049	72.5095555
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
49.4	44.69	18.8	197239.7	2207.7	81.17061731	0.000350277	39581.48378	26.42163239	98153.45	46004.27603	0.001548776	0.0057485	9.75849975	1008.73817
49.4	49.91	3.76	132655.1	2465.6	54.5919412	0.000235582	26620.84024	17.77007801	66013.88	30940.54	0.001041642	0.0038662	6.563156253	678.434838
40.84	49.91	18.8	186544.1	2038.3	76.76904559	0.000331283	37435.1315	24.98888845	92830.96	43509.64033	0.001464792	0.0054368	9.229333681	954.038157
49.4	44.69	16.92	187301.1	2207.7	77.08058343	0.000332627	37587.04768	25.09029631	93207.68	43686.20758	0.001470736	0.0054589	9.266787406	957.909757
42.09	49.91	18.8	190564.9	2100.7	78.42374065	0.000338423	38242.01567	25.52750385	94831.86	44447.45565	0.001496364	0.005554	9.428264549	974.601683
49.4	43.08	18.8	192040.9	2128.2	79.03117068	0.000341045	38538.21869	25.72522679	95566.38	44791.72282	0.001507954	0.005597	9.501291045	982.150447
49.4	49.91	15.04	193173.6	2465.6	79.49729178	0.000343056	38765.51479	25.87695263	96130.02	45055.90171	0.001516848	0.00563	9.557329089	987.943111
49.4	44.69	18.8	197239.7	2207.7	81.17061731	0.000350277	39581.48378	26.42163239	98153.45	46004.27603	0.001548776	0.0057485	9.75849975	1008.73817
49.4	49.91	16.92	203649	2465.6	83.80827057	0.000361659	40867.69095	27.28020791	101343	47499.19295	0.001599104	0.0059353	10.07560389	1041.51729
49.4	49.91	18.8	214112.3	2465.6	88.11424919	0.000380241	42967.42887	28.68183559	106549.9	49939.65029	0.001681264	0.0062403	10.59327756	1095.02932

Table 4-19: input & output's Cube, Appendix D, Page 458

Diagram 4.20 depicts the scatter plot for the cube model. The plots exhibit a definitive positive trend, suggesting that as the length increases, so do the environmental impacts. The scatter plots' trend lines are pronounced, and the data points form a tight cluster around these lines, supporting the findings from the statistical analysis. Outputs such as "Carcinogenics," "Non-carcinogenics," "Ozone depletion," "Fossil fuel depletion," "Respiratory effects," "Smog," "Thermal Load (kWh)," and "Global warming" are notably influenced by Length, as shown by the significant upward trends. This corresponds with high correlation coefficients, demonstrating a heightened sensitivity to changes in the Length dimension. In the comparison of the three input variables—Length, Width, and Height—Length appears to exert the most substantial influence on the outputs, with Height following and Width showing the least impact. The correlation analysis between these input variables (X, Y, Z dimensions) and the

outputs for energy consumption (cooling, heating, etc.) reveals that the Length has a profound impact on Environmental Impact categories. The correlation coefficient for Length with heating is notably strong, while its relationship with cooling is similarly positive. This indicates that as Length increases, there is a tendency for both heating and cooling demands to rise. Conversely, the Width shows a less pronounced, and in some cases inverse, relationship with these environmental impacts. For energy efficiency optimization leading to reduced environmental impacts, careful consideration should be focused on the cube's Length in the design and structural management, as this dimension significantly affects heating and cooling demands.

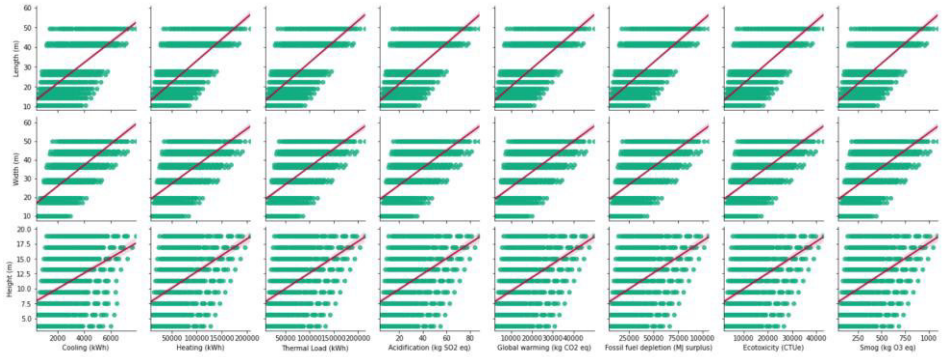


Diagram 4-59: scatter plots (Cube), Appendix C, Page420

One of the key goals of this scholarly research is to derive a mathematical formula that defines the relationship between the input variables (length, width, and height) of a cube and its associated outputs, which encompass cooling, heating, and a range of environmental impact metrics. It is essential to note that the effectiveness of this formula is reliant on consistent environmental conditions, exemplified by the climatic conditions of Boston for the purpose of our study. Additionally, the deliberate exclusion of certain variables is intended to diminish the impact of extraneous factors on the variability of the results. The formulas developed herein will elucidate the intricate links between the cube's length, width, and height and their collective influence on the measured outputs.

Cooling (kWh) = -2690.386310813715 + (70.745206511526 26 * Length (m)) + (77.50194873056414 * Width (m)) + (117.84102310586006 * Height (m))

Heating (kWh) = -72506.56606484 66 + (1947.88426673401 89 * Length (m)) + (1768.47337463256 74 * Width (m)) + (3242.86261242691 85 * Height (m))

Thermal Load (kWh) = -75196.95237702856 + (2018.6294733133022 * Length (m)) + (1845.97532340824 * Width (m)) + (3360.703635383338 * Height (m))

Acidification (kg SO2 eq) = -30.94602292956616 + (0.8307325229647099 * Length (m)) + (0.7596796529659137 * Width (m)) + (1.3830402492387595 * Height (m))

Global warming (kg CO2 eq) = -17538.9744247183 + (470.82613837730895 * Length (m)) + (430.55619890688297 * Width (m)) + (783.8521808126087 * Height (m))

Fossil fuel depletion (MJ surplus) = -37420.66902401942 + (1004.5415806854379 * Length (m)) + (918.6227555894478 * Width (m)) + (1672.4052564727951 * Height (m))

Ecotoxicity (CTUe) = -15090.306633097296 + (405.09271676210903 * Length (m)) + (370.4449819653313 * Width (m)) + (674.4162730008053 * Height (m))

Smog (kg O3 eq) = -384.5780088295366 + (10.323829342425338 * Length (m)) + (9.44082827543138 * Width (m)) + (17.187567733698444 * Height (m))

The accuracy of the developed equations was thoroughly assessed using Python as the computational instrument. The results of this analytical process have exhibited an impressively high level of precision, measured to be 95% for all the equations formulated (Diagram 4.21).

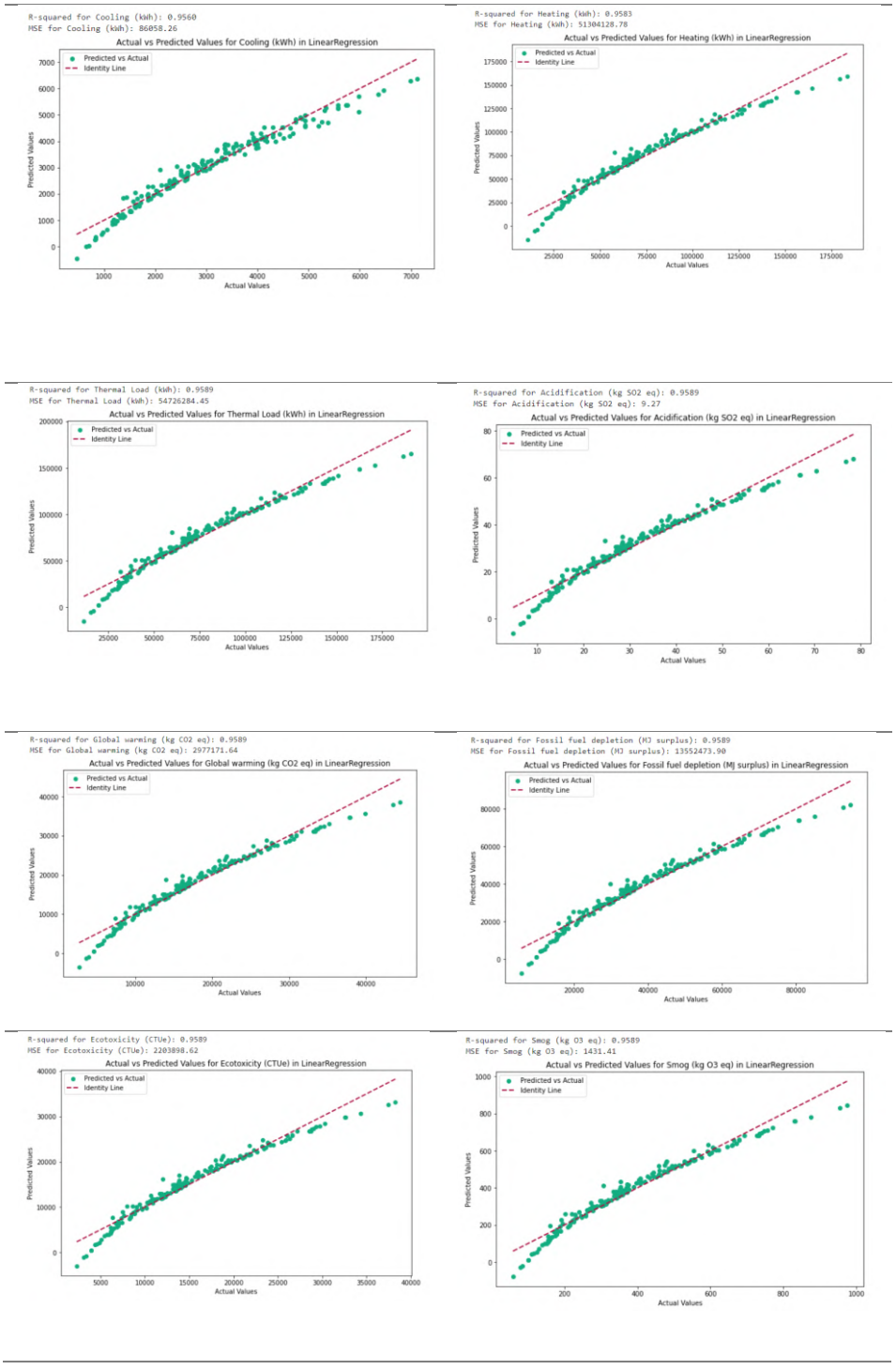


Diagram 4-62: Actual values vs predicted values (Cube), Appendix C, Page 421

During the most recent stage of thorough examination, an in-depth comparative analysis of the cube's dimensions—length, width, and height—was conducted using a model evaluation metric to determine their individual sensitivities and respective impacts on the output variables. This comparative study provides crucial insights that are fundamental in shaping the decision-making process integral to design optimization. It enables the strategic determination of dimensions that align with environmental sustainability. In this analysis, a deliberately selected random sample of 20 data points was scrutinized. The results underscore the disproportionately significant effect of the variable X (Lengh) on model outcomes in contrast to width and length. Furthermore, the study suggests that changes in X (Lengh) are more likely to significantly influence the aggregate output data, as opposed to variations in width or length (Diagram 4.22).

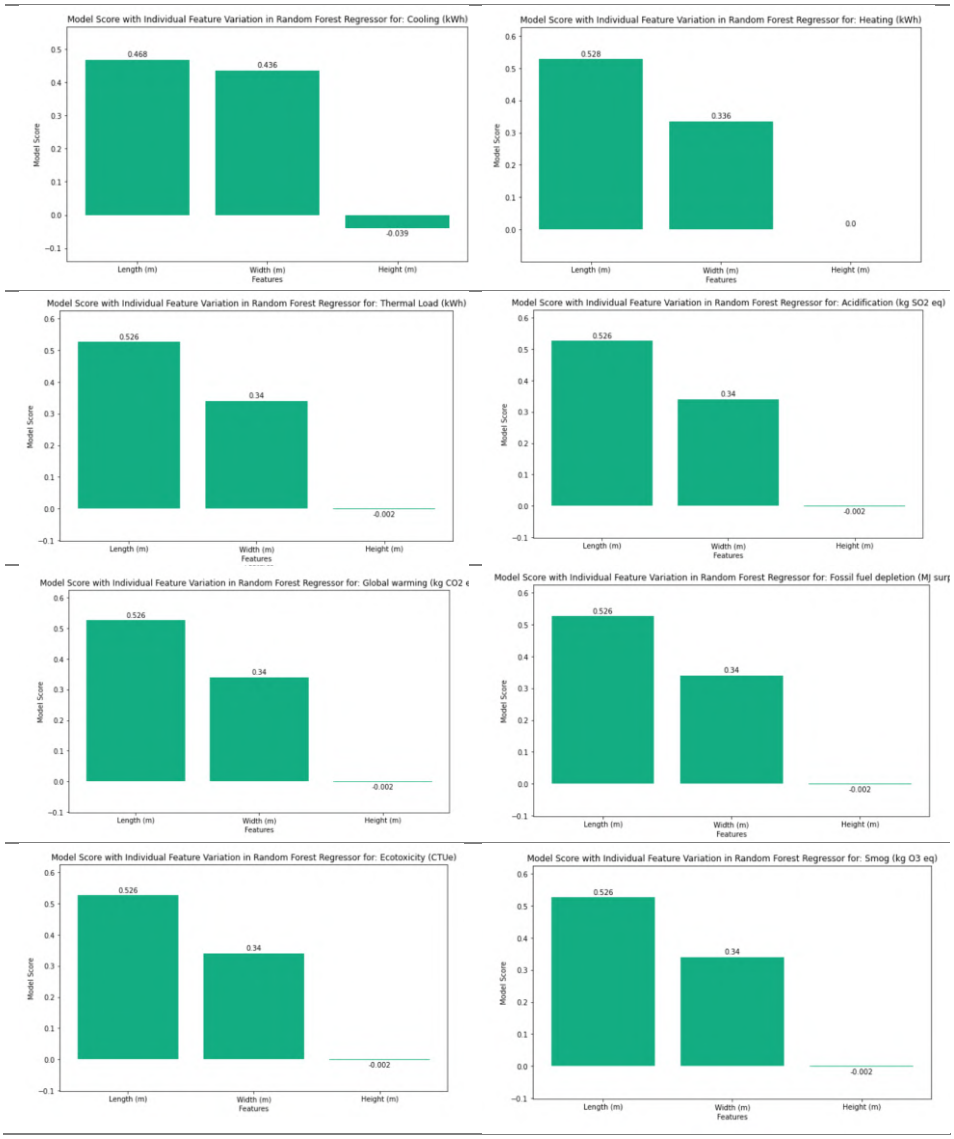


Diagram 4-65: Model Score with individual Features in Random Data (Cube), Appendix C, Page 423

The next analysis phase compared the sensitivities of a cube's dimensions—Length, Width, and Height—using advanced statistical methods like Random Forest (RF),

XGBoost, and Recursive Feature Elimination (RFE). Each method yielded divergent results due to their unique evaluation approaches. RFE suggests Width is pivotal based on model accuracy when features are eliminated sequentially. RF deems Length crucial, considering how it influences the model across decision trees. XGBoost, assessing feature contributions via metrics like 'gain', emphasizes Width's significance. These variations highlight that different models prioritize features based on their specific data handling and interpretive algorithms, leading to discrepancies in feature importance rankings. Therefore, a comprehensive review of feature importance across methods, supplemented by domain expertise, is essential to discern truly influential features. (Diagram 4.23).

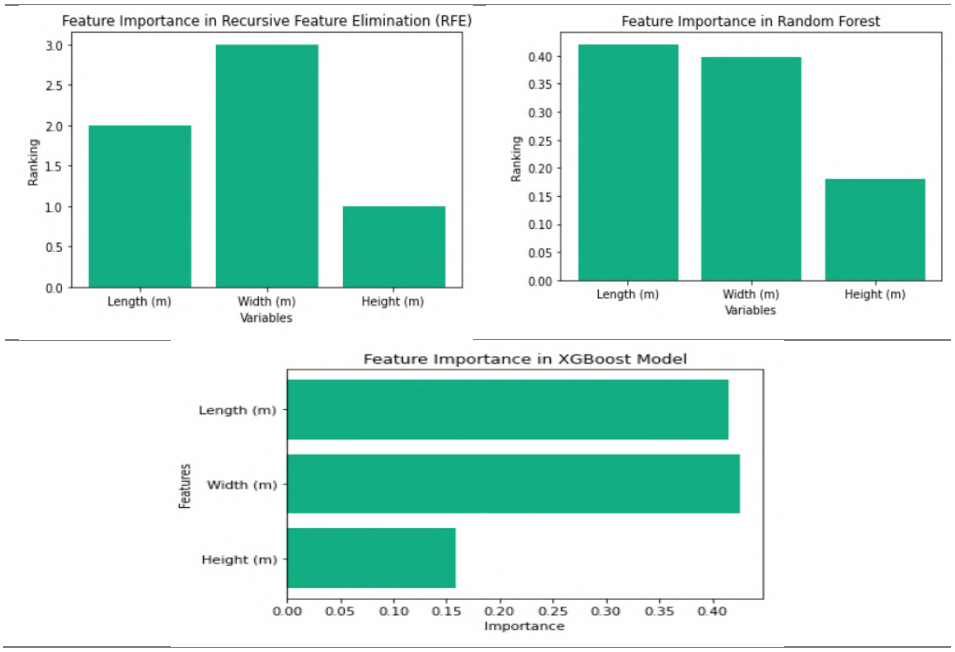
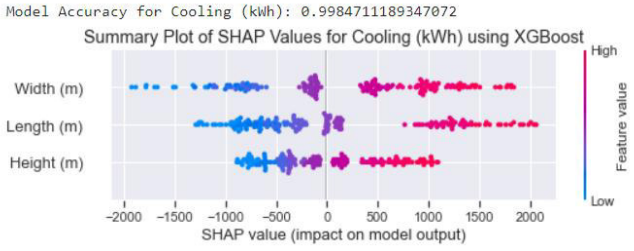
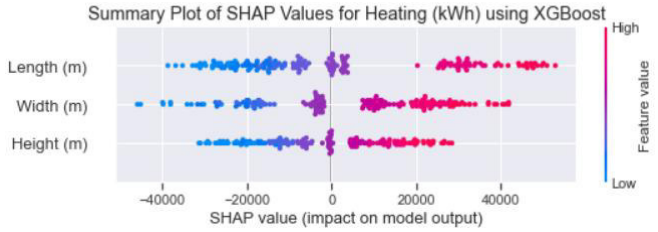


Diagram 4-68: FRE & XGBoost &RF (Cube), Appendix C, page426

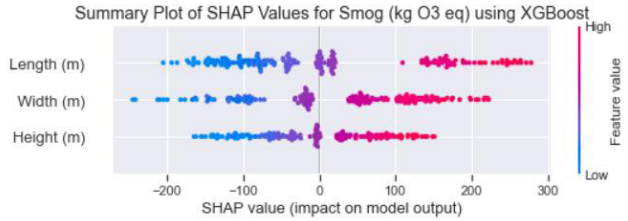
The SHAP summary plots, derived from the XGBoost model for the cube analysis, provide insight into the varying levels of importance of the dimensions 'Length (m)', 'Width (m)', and 'Height (m)' in relation to environmental and energy consumption outputs. The plots reveal a more extensive spread of SHAP values for 'Length', indicating its significant and diverse impact on outputs such as heating, thermal load, acidification, global warming, and fossil fuel depletion. In contrast, 'Width' demonstrates a greater effect on cooling systems. Considering the climatic conditions of Boston, which predominantly experiences colder temperatures throughout the year, heating presents a more substantial concern. Therefore, despite 'Width's larger impact on cooling, 'Length' emerges as the pivotal dimension to prioritize in the design phase to address the prevalent heating challenges in Boston's climate (Diagram 4.24).



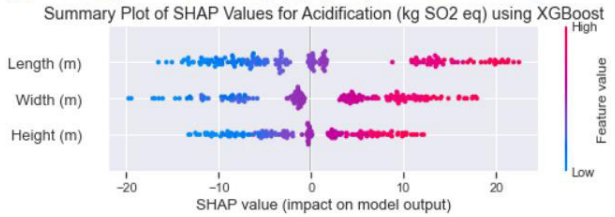
```
Model Accuracy for Heating (kWh): 0.9974740163493085
```



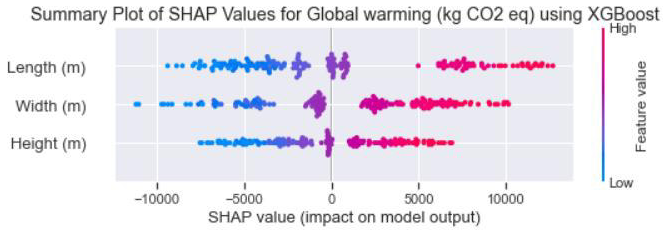

```
Model Accuracy for Smog (kg O3 eq): 0.9977121792754181
```



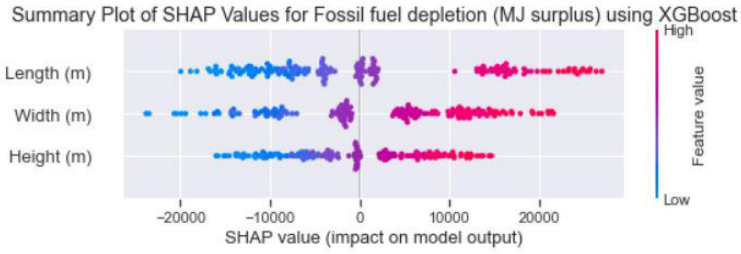

```
Model Accuracy for Acidification (kg SO2 eq): 0.9976512190831744
```



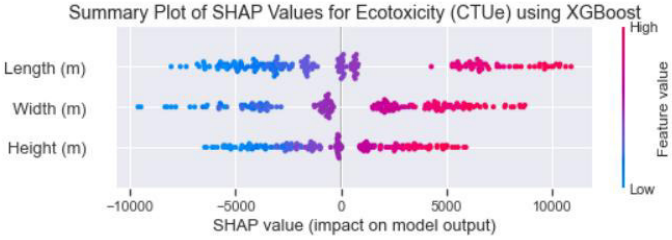

```
Model Accuracy for Global warming (kg CO2 eq): 0.9976731310183415
```




```
Model Accuracy for Fossil fuel depletion (MJ surplus): 0.9976731336338395
```




```
Model Accuracy for Ecotoxicity (CTUe): 0.9977121846450938
```



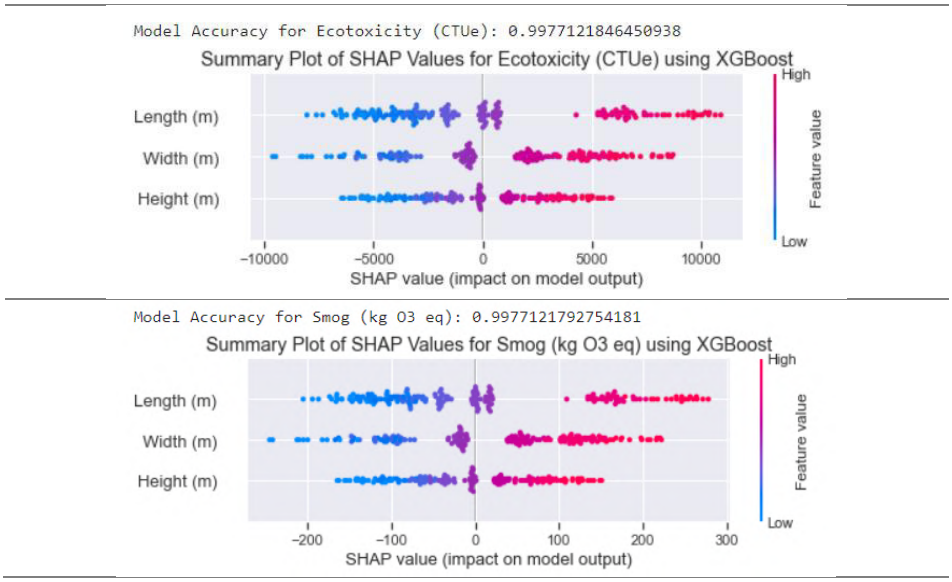


Diagram 4-71: SHAP diagram (Cube), Appendix C, Page 427

In heatmap diagram 4.25, the parameters include the length, width, and height of a building, along with heating and cooling requirements, thermal load, acidification, global warming potential, fossil fuel depletion, ecotoxicity, and smog production.

This analysis highlights the varying importance of a cube's dimensions in influencing environmental impacts. while Length has a moderate positive correlation with environmental impacts. Increasing the cube's length tends to worsen environmental consequences, Changes in width and height show almost no correlation with the environmental outputs. This suggests that, within this model, these dimensions don't significantly influence environmental performance.

The environmental impact outputs themselves are highly correlated. This indicates they are likely driven by common factors and will tend to increase or decrease in tandem. For cubes, focusing on optimizing the length dimension will have the most potential to improve environmental performance. Altering width and height, within the context of this analysis, may not significantly change the environmental impacts measured.

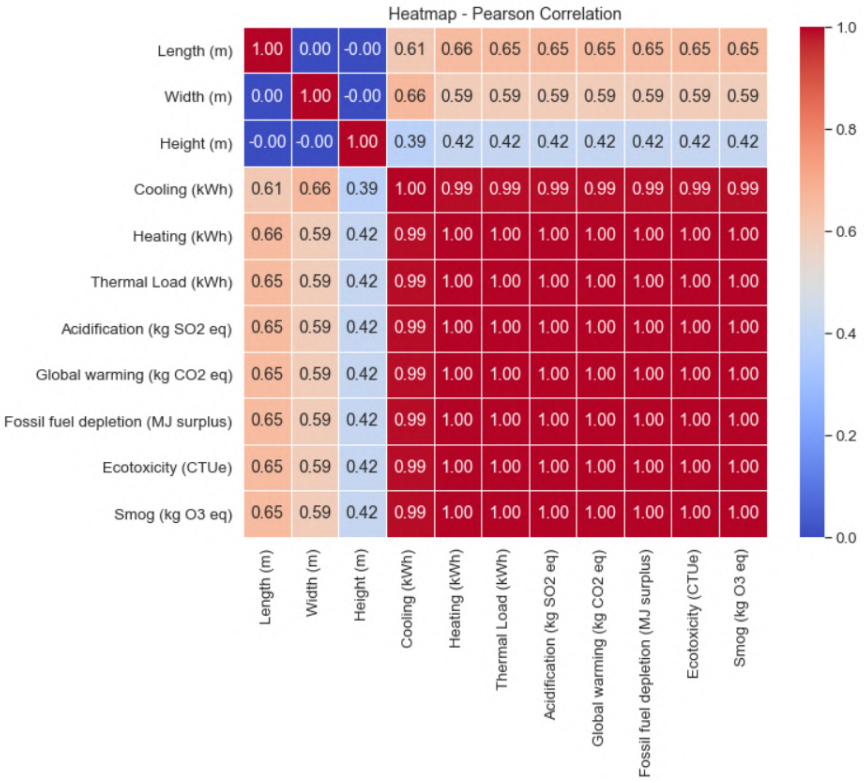


Diagram 4-74: Heatmap- Pearson correlation (Cube), Appendix C, Page 429

This Spearman correlation heatmap, a non-parametric measure, delves into the relationships between a cube's dimensions (length, width, and height) and various environmental impact metrics. It sheds light on how adjustments to the cube's physical properties might be linked to changes in its environmental footprint. The analysis reveals a critical finding: a moderate positive correlation (around 0.63) exists between the cube's length and environmental impacts. This suggests that as the length increases, the environmental consequences tend to rise as well. Therefore, for cubic structures, managing the length dimension becomes particularly important for minimizing environmental impact. both width and height exhibit no correlation with the environmental metrics within this dataset. This implies that, in this specific case, changes in these dimensions might not have a predictable or consistent influence on the environmental factors being measured. Another key takeaway lies in the high correlation coefficients observed between the environmental impact measures themselves (cooling, heating, thermal load, etc.). This indicates that these factors are closely intertwined; a change in one is highly likely to be accompanied by changes in the others, at least in terms of their ranking within the data. While the Spearman correlation doesn't establish causation, it offers valuable insights for environmentally conscious design. It highlights that length, among all the dimensions, might have a more consistent and significant association with the studied environmental impacts, making it a potential focus for optimization efforts aimed at reducing the environmental footprint of cubic structures (Diagram 4.26).

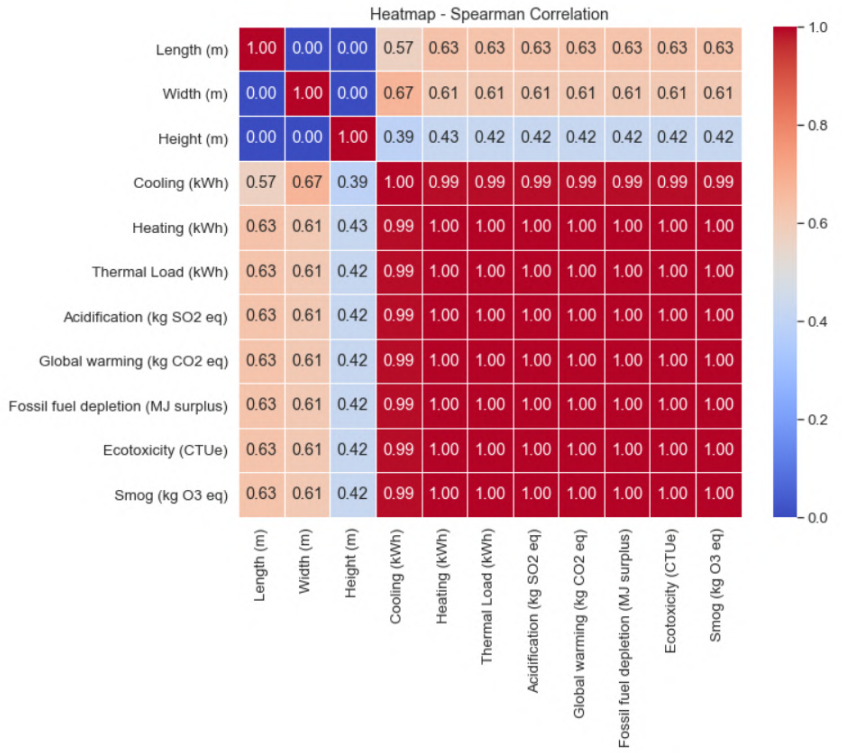
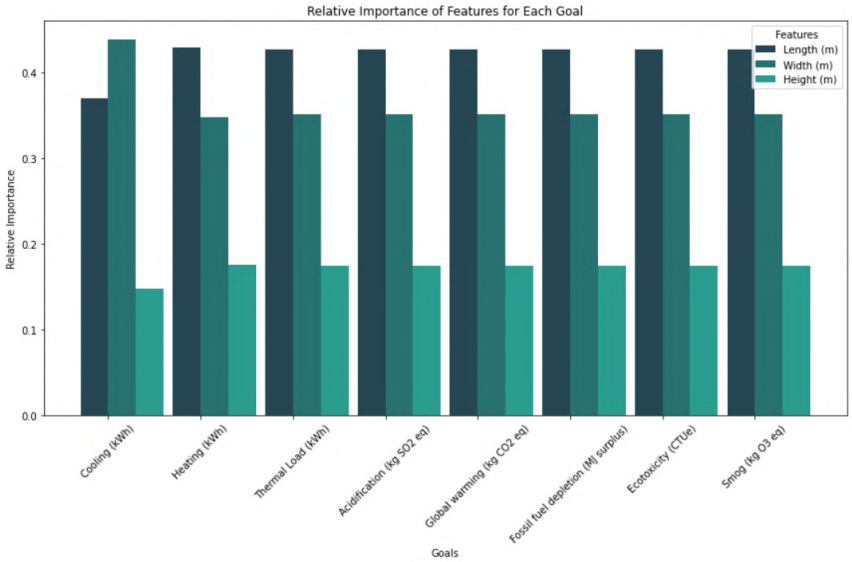


Diagram 4-77: Heatmap-Spearman Correlation, Appendix C, Page 429

Note: It warrants emphasis that a multitude of real-world factors critically modulate these sensitivities. These include the precise geographical setting of a structure, the intended functionality of the edifice, the selection of construction materials, and the particular environmental impacts under scrutiny. Each of these elements exerts a distinct influence on the degree to which the aforementioned dimensions affect environmental outcomes.

The diagram elucidates that the length dimension exhibits a more pronounced effect on the outputs, particularly within the cooling metrics where the impact of width is deemed more significant. This observation is consistent with the case study situated within the climatic context of Boston, where longitudinal expansion could potentially increase surface exposure, thereby influencing the thermal regulation requirements of structures. Conversely, the width's notable influence on cooling may be attributed to its role in affecting the building's aspect ratio, which is a critical factor in thermal performance due to its impact on shadow casting and surface area exposed to solar gain. Overall, considering the predominance of length's impact across a majority of the outputs, it can be deduced that length is the most critical dimension concerning output factors, especially within the framework of Boston's distinctive climatic conditions. (Diagram 4.27).

Diagram 4-83: Relative importance of Features for each Goal, Appendix C, Page430



4.1.7 Summary and Conclusion

In the culmination of this research, the results from a comprehensive suite of analyses underscore the pivotal role of geometry in achieving environmentally sustainable buildings. Among the geometries assessed, the sphere has emerged as the most efficient shape, notably outperforming the cube and cask in both cooling and heating scenarios, with lower energy consumption leading to reduced environmental impacts. Various modeling techniques and statistical analyses were employed, including Grasshopper for geometric modeling, OpenLCA for life cycle assessment, and advanced machine learning algorithms for sensitivity analysis. These methods quantified the environmental impacts of different geometric forms and their associated energy consumption. Utilizing the OpenLCA framework with the Ecoinvent database enabled a detailed life cycle assessment, highlighting the significant influence of geometric parameters, such as radius, on environmental impact categories. For example, the normalized impacts, based on CO_2 equivalents, showed the radius's marked dominance over height in determining environmental outcomes. Quantitative results have been refined into robust mathematical models that correlate geometric inputs with energy and environmental outputs. These models have been rigorously tested for accuracy and exhibit a high degree of precision, validated through Python's computational analytics, with an accuracy level of 96% across all formulas. Furthermore, sensitivity analyses using Feature Importance in Random Forest (FRF) and Extreme Gradient Boosting (XGBoost) illustrated the predominant influence of the radius on environmental impact. The final assessment of feature importance reinforces the sphere as the optimal geometry, confirming the radius as a critical determinant of environmental impact, more so than height. In conclusion, this study highlights the importance of geometric considerations in architectural design, with a special emphasis on the radius as a significant factor in energy efficiency and environmental impact reduction. The sphere, with its favorable surface area-to-volume ratio, is identified as the most sustainable geometric form among those examined, advocating for its inclusion in design practices aimed at creating positive environmental buildings. These

findings not only contribute to the progress of sustainable architectural design but also provide a predictive framework for researchers and designers to estimate environmental impacts without extensive modeling, thereby conserving time and resources. The sphere is recommended for its potential to bolster ecological conservation and improve public health outcomes in the built environment.

4.2 Section 2: Materials

4.2.1 Introduction

Climate mitigation represents a concerted human endeavor to decrease or neutralize greenhouse gas emissions, whereas climate adaptation denotes the recalibration of human systems to lessen the negative repercussions and capitalize on the beneficial prospects arising from present or anticipated climatic fluctuations. Consequently, policies addressing climate change span a variety of initiatives designed to limit emissions of greenhouse gases and diminish carbon footprints, thereby reducing the severity of climate change's impact. These measures also strive to lay the groundwork for societal resilience to the vicissitudes and potential hazards introduced by climate variability. Pertinent data from the Intergovernmental Panel on Climate Change (IPCC) indicate the highest atmospheric concentration of greenhouse gases in over two million years, with carbon dioxide levels in 2019 surging to 148% above pre-industrial figures. Within the realm of urban development, the construction sector emerges as a substantial contributor to environmental degradation, primarily through its reliance on building materials sourced from non-renewable resources that also precipitate indoor air pollution, thereby affecting both internal and external environmental quality. Prioritizing sustainable materials and construction techniques is instrumental in attenuating the environmental impact of building activities, a crucial step in the global campaign to address climate change.

This chapter critically assesses the environmental implications of cladding systems within architectural constructs, scrutinizing the intricate decision-making involved in material selection and its ramifications for ecological sustainability. The examination delineates how the choice of cladding materials during the operational phase of a building influences energy consumption and, consequently, the overall environmental impact. Furthermore, the study probes the nexus between the choice of cladding materials and their contribution to sustainability and conservation objectives. In the quest to discern the most eco-compatible cladding system for a building's operational phase, the analysis juxtaposes three distinct cladding types: aluminum, polycarbonate, and an innovative hybrid system integrating both materials. Indeed, in the subsequent section, the researcher extends the investigative lens to encompass critical performance indicators such as the Adaptive Solar Envelope (ASE) and Spatial Daylight Autonomy (sDA). The integration of these metrics is pivotal for measuring the potential of edifices to contribute constructively to the built and natural milieu, thus advancing the pursuit of 'positive buildings'—those that not only attenuate environmental damage but also engender sustainability gains.

The analysis is informed by attributes including the low density, robustness, and reusability of aluminum, as well as polycarbonate's resistance to impact, thermal insulative capacity, and propensity for light diffusion. This comprehensive review

illuminates the environmental ramifications of diverse material composites and gauges, identifying configurations that amplify ecological impact. The in-depth evaluation of each system's environmental footprint markedly bolsters the discourse on sustainable architectural methods. It furnishes critical perspectives to architects, engineers, and environmental specialists on the ecological dimensions of cladding systems, guiding the industry toward more ecologically considerate design alternatives.

4.2.2 Methodology

In the designated section of the research, the analysis centers on the optimized geometric model, emphasizing the spherical form as introduced in Section One. This model represents a large office building configured for Boston's climatic conditions and serves as the primary focus of the case study. To ensure consistency in the analysis, the dimensions of the model are kept constant. The investigation delves into the influence of material properties on the environmental performance of the building.

Utilizing the Rhino and Grasshopper plugins, the study models two cladding systems: aluminum and polycarbonate. Key variables for each system include thickness, layering, and physical attributes. The materials were chosen based on their inclusion in Environmental Product Declaration (EPD) libraries, which detail the environmental impacts of materials during the manufacturing (A) and end-of-life (C) stages. Nonetheless, the focus of this research is on the use phase (B6 stage), assessing how the selected cladding systems affect the building's operational environmental impact.

The evaluation was grounded in a standardized approach, where comparisons were based on a functional unit of one square meter, which was then extrapolated to a total cladding area of 1,519.5929 m^2. The assessment period was designed to capture long-term effects, reflecting the sustainability and environmental impacts of each material used in construction over an assumed service life of 50 years. During the operational phase, which is known for significant resource consumption and environmental impact due to factors such as energy usage for heating, cooling, and maintenance, special attention was given to understanding the indirect effects of each cladding type. This targeted focus allowed for a detailed exploration of how different cladding materials influence building sustainability within the predefined life cycle stages.

Following the initial environmental impact assessment, the research conducts a comparative analysis between the aluminum and polycarbonate cladding systems. Subsequently, a combined cladding system, merging both aluminum and polycarbonate, was modeled. An optimized model was derived through WALLACEI component from a comprehensive analysis of 1,104,150,528 iterations, chosen for its reduced environmental impact during the use phase, and evaluated against factors like Annual Sunlight Exposure (ASE) and Spatial Daylight Autonomy (SDA) to support sustainable building design.

The optimized hybrid model, integrating the advantages of both aluminum and polycarbonate cladding, underwent comparison with the single-material systems to verify its superior sustainability attributes during the use phase. This evaluative process was crucial for determining the hybrid cladding system's optimization and sustainability.

The methodology of this research is systematically segmented into three phases: initial analysis of an aluminum cladding system, followed by a polycarbonate system analysis, and culminating in the examination of a hybrid system combining both materials. Upon

interpreting the results, principles for designing spatial structures for large office buildings in Boston were formulated. The sequence of these procedural steps is visually represented in Diagram 4.28, outlining the analytical process undertaken in the study.

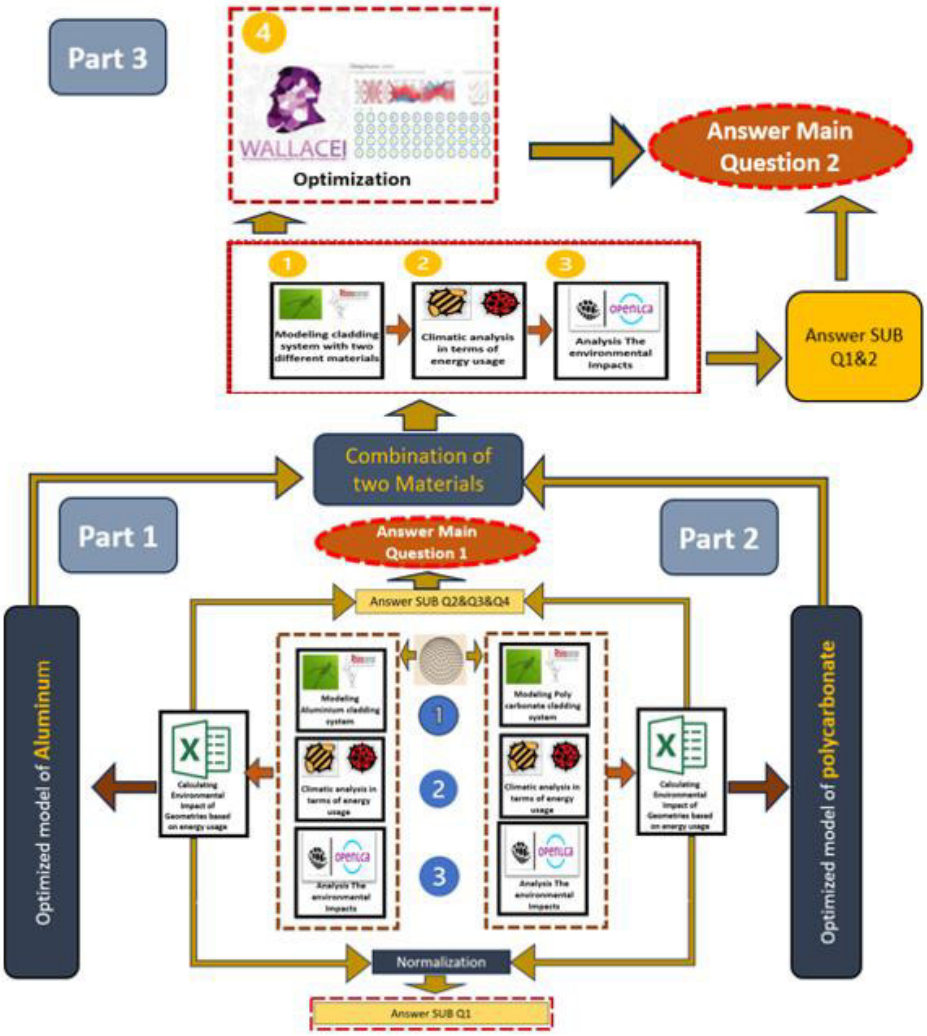


Diagram 4-86: The methodology of section 2, Appendix C, Page 431

4.2.3 Aluminum Cladding system

4.2.3.1 A review of Aluminum

After steel, aluminum is the most highly produced metal and the most produced non-ferrous metal(Brough & Jouhara, 2020)(T.J. Brown et al. 2018). Aluminum was intrinsically tied with the modern era and modernism. This was due to its association with science and technology, as well as its intention to build markets for the metal and create a mystery surrounding it. Some have dubbed the current age 'The Aluminum Age' owing to the exponential expansion in aluminum production and use in everyday items (Perchard 2017). The physical properties of aluminum, such as its lightweight nature, corrosion resistance, and strength, have led to its increasing utilization across various industrial sectors. In the construction industry, particularly, there has been a notable rise in the use of aluminum as a preferred material, especially in cladding systems. This trend reflects the growing recognition of aluminum's advantages, including its durability, aesthetic flexibility, and environmental benefits, which align well with the evolving demands for sustainable and innovative building solutions. A cladding system is a crucial component of a building's sustainable performance (Abu Dabous et al. 2022).

Cladding design is primarily the responsibility of the architect('McMullin, 'Price, and "Simchuk S" (Eds.) 2017).Architects, armed with knowledge of materials and their environmental impacts, can make more informed decisions during the design phase, selecting appropriate materials to potentially reduce the environmental footprint of the construction sector. A thorough understanding of the lifecycle and ecological consequences of various construction materials enables architects to integrate sustainability into their design choices, thereby minimizing the negative environmental impacts associated with building construction and operation. Aluminum cladding systems represent a significant advancement in the construction industry, redefining the boundaries of architectural design and sustainability. these cladding systems have garnered significant attention in the realm of architectural engineering, owing to their distinctive attributes that align with contemporary sustainable building practices. they are acclaimed for their lightweight nature, corrosion resistance, and high durability, which not only facilitate ease of installation but also extend the lifespan of building envelopes. The advent of aluminum cladding in roofing technology represents a paradigm shift towards eco-friendly construction materials that offer energy efficiency, recyclability, and a reduced environmental footprint. Aluminum, as a contemporary construction material, rivals traditional materials like steel or concrete, offering a harmonious blend of durability and aesthetic appeal. It has emerged as a pivotal element in sustainable construction practices, where its physical and mechanical properties contribute to the environmental and economic efficiency of buildings. By integrating aluminum cladding systems, buildings can achieve a green performance, encompassing ecological benefits and cost-effectiveness, while also maintaining functionality and structural stability (Efthymiou, Cöcen, and Ermolli 2010).

Moreover, the adaptability of aluminum cladding systems to various architectural styles and their ability to provide enhanced thermal insulation has catalyzed their adoption in modern construction. This has led to an evolution in roofing designs, integrating aesthetics with functionality while addressing the pressing demands of energy conservation and climate adaptability. The integration of advanced fabrication techniques and surface treatments has further augmented the performance and

aesthetic appeal of aluminum roofing systems, making them a preferred choice for sustainable building designs. In architectural engineering, a cladding system is an assembly comprising various elements such as cladding, insulation, cavities, cavity barriers, mounts, fasteners, and substrate, along with specific details like opening frames (Guillaume et al. 2018).

This research is dedicated to assessing the environmental impact of a cladding system during the use phase (B6) of the building's lifecycle, emphasizing the importance of a holistic lifecycle perspective to align with the principles of positive building development. Recognizing the necessity of comprehensive lifecycle analysis, the researcher has selected a cladding system that is certified by an Environmental Product Declaration (EPD), encompassing stages A (manufacturing) and C (end-of-life). The Kalzip cladding system, which is EPD-certified and has been evaluated for LEED certification, is chosen for this purpose. This selection ensures that the system's environmental performance is rigorously documented and recognized, facilitating a more realistic and credible assessment of sustainability. The forthcoming detailed examination of the Kalzip system will provide an in-depth analysis of its attributes and sustainability credentials, shedding light on its environmental impact across the entire lifecycle, with a special focus on the operational phase. This approach enhances the authenticity and relevance of the sustainability assessment, contributing to a more accurate representation of the building's environmental footprint.

4.2.3.1.1 Kalzip cladding system

Aluminum cladding systems for spatial structure domes, such as geodesic domes or other architectural forms, are often chosen for their durability, lightweight, and aesthetic flexibility. The layers of an aluminum cladding system can vary based on specific project requirements, environmental considerations, and architectural goals. However, a typical aluminum cladding system might include the following layers:

- **Structural Support Layer**: This is the primary layer that provides the framework for the dome. It can be made of steel, aluminum, or another durable material capable of supporting the cladding system.
- **Thermal Insulation Layer:** To improve energy efficiency, a layer of thermal insulation is often placed between the structural support and the aluminum panels. This layer helps in maintaining the internal temperature of the structure.
- **Vapor Barrier:** A vapor barrier might be included to prevent moisture from penetrating the insulation, which can compromise its effectiveness and potentially damage the structure.
- **Aluminum Panels:** These are the external layers visible from the outside. Aluminum panels can be prefabricated in various shapes and sizes to fit the geometric complexity of a dome. They can be anodized, painted, or treated in other ways to achieve the desired aesthetic and protective properties.
- **Weatherproofing Sealants and Gaskets:** To ensure the cladding is watertight and weatherproof, sealants and gaskets are applied at the joints and edges of aluminum panels. This layer prevents water ingress and protects the internal layers from the elements.
- Finish Coatings: The outermost layer might include finish coatings for additional protection against corrosion, UV radiation, and other

environmental factors. These coatings can also provide color and texture to the aluminum panels, contributing to the overall visual impact of the dome.

- **Fastening System:** Although not a layer in the traditional sense, the method used to attach the aluminum panels to the structure is crucial. Mechanical fasteners, adhesives, or a combination of both might be employed, depending on the design requirements and structural calculations.

The regulations in Massachusetts mandate that all companies utilize materials with Environmental Product Declarations (EPD), necessitating the selection of a compliant provider for a case study located in Boston. Consequently, Kalzip Company was chosen, a distinguished leader in the supply of aluminum building envelopes, renowned for its production of roof and façade systems via advanced roll forming technology since 1968. To date, Kalzip has installed over 110 million square meters of profile sheets globally, supported by international sales offices and a worldwide mobile production fleet, marking its presence globally. This company boasts over fifty years of expertise in the aluminum cladding system sector. European EPD, carried out by the Institution for Building and the environment (IBU e.V.). Kalzip's products have undergone assessment in accordance with BRE, ECO* and FDES - the most important European building certification programs. They represent a type-III environmental product certification according to ISO 14025 and are recognized and verified by independent examiners. Kalzip products are made, for the most part, **from recycled aluminum**. The recycled content of the aluminum coils used in production, both coated and uncoated, lies somewhere between 75% and 95%. The greatest economic and environmental advantage of recycled aluminum is that the recycling process requires less than a tenth of the energy required for primary production of the same amount of aluminum.

In the following, the environmental impacts of 1 m2 Standing seam roofing cladding system made of polyvinylidene fluoride (PVDF)-coated aluminum. The analysis refers to 1 m² system consisting of 1 mm standing seam aluminum sheet, 200 mm rock wool insulation, 1.75 E-180 clips made of plastic-coated steel, a vapor barrier SKBitumen and 3.5 fasteners made of stainless steel, including packaging. in A&C&D stages are analyzed using the example of the global warming potential (GWP) to identify the responsible sources along the life cycle (data have been extracted from Environmental Product Declaration as per ISO 14025 and EN 15804+A2, Kalzip GmbH, https://epd-online.com) (Table 4.8).

Table 4-22: global warming potential (GWP) of 1 m2 aluminum in A&C&D stages, Appendix D, Page 458

Parameter	Unit	A1-A3	A5	C1	C2	C3	C4	D
GWP-total	kg CO2 eq	2.45E+01	3.77E-01	1.10E-03	8.96E-02	3.27E+00	1.23E-01	-5.35E+00
GWP-fossil	kg CO2 eq	2.48E+01	8.97E-02	1.10E-03	8.90E-02	3.27E+00	1.22E-01	-5.35E+00
GWP-biogenic	kg CO2 eq	-2.87E-01	2.87E-01	0	0	0	0	0
GWP-luluc	kg CO2 eq	7.75E-03	1.17E-05	7.16E-08	6.01E-04	1.41E-05	2.26E-04	-1.16E-03
ODP	kg CFC11 eq	3.79E-07	3.83E-14	1.09E-14	8.76E-15	8.37E-13	2.87E-13	4.75E-11
AP	mol H^+ eq	1.36E-01	6.00E-05	1.62E-06	3.16E-04	1.21E-03	8.68E-04	-2.46E-02
EP-freshwater	kg P eq	2.26E-05	1.28E-08	4.95E-10	3.19E-07	1.78E-07	2.07E-07	-3.11E-06
EP-marine	kg N eq	1.70E-02	1.94E-05	4.43E-07	1.46E-04	5.31E-04	2.22E-04	-3.25E-03
EP-terrestrial	mol N eq	3.48E-01	2.84E-04	4.74E-06	1.63E-03	6.30E-03	2.44E-03	-3.53E-02
POCP	kg NMVOC eq	5.34E-02	5.11E-05	1.25E-06	2.85E-04	1.38E-03	6.74E-04	-9.96E-03
ADPE	kg Sb eq	1.25E-04	9.58E-10	1.31E-10	8.99E-09	1.71E-08	1.25E-08	2.27E-05
ADPF	MJ	3.59E+02	1.20E-01	2.34E-02	1.17E+00	1.44E+00	1.60E+00	-7.08E+01
WDP	m^3 world eq deprived	2.92E+00	4.02E-02	8.24E-05	9.95E-04	3.05E-01	1.34E-02	-7.39E-01

GWP = Global warming potential; ODP = Depletion potential of the stratospheric ozone layer; AP = Acidification potential of land and water; EP =Eutrophication potential; POCP = Formation potential of tropospheric ozone photochemical oxidants; ADPE = Abiotic depletion potential for non-fossil resources; ADPF = Abiotic depletion potential for fossil resources; WDP = Water (user) deprivation potential)

Diagram 4.29 shows a LCA interpretation of Kalzip system.

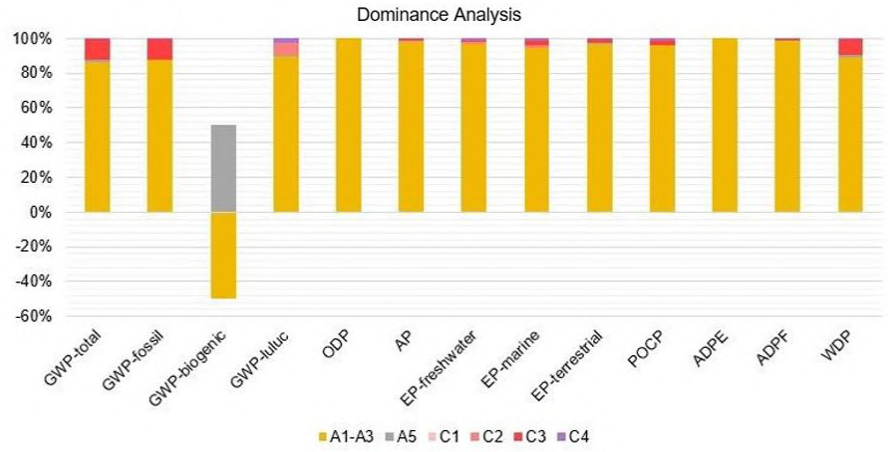
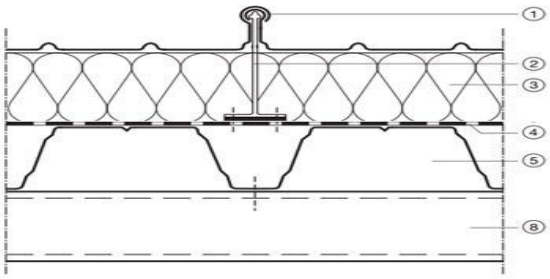


Diagram 4-29: LCA interpretation of Klazip system, Appendix C, Page 432

As table 4.9 shows Modules A1–A3 have a dominant influence on all environmental indicators considered. The production phase (modules A1–A3)) implies a contribution to the total global warming potential of 86%. Here, the provided rock wool (35%%) , primary aluminum sheet (23%%) and secondary aluminum sheet (23%%) of the manufactured roofing and wall cladding, dominate the total emissions of the module. All other materials contribute less than 6% each to the manufacturing phase. Both transport to the company (A2)) and disposal transport (C2) have no major relevance in terms of GWP, at 1.7% and 0.3%, respectively. Product installation at the construction site (A5) has a contribution of 1.3%. The negative contribution to the GWP (biogenic) in A1–A3 and the positive contribution in A5 can be explained using waste treatment at the end of the life of the product, which accounts for 12% of the total GWP. This is mainly caused by the energy recovery of the bitumen sheeting (84%). Since this is a worst-case consideration, the values of the specific products, all of which are covered by the EPD, are usually better than the calculated example system. It can be assumed that the environmental impacts are reduced for other possible configurations.

The Environmental Product Declaration (EPD) for the Kalzip aluminum standing seam roofing and wall cladding system refers to a declared unit of 1 square meter (m^2) of material, including packaging. The EPD indicates a heat transfer coefficient, also known as the U-value, which is 0.19 W/(m^2K). The U-value is a measure of thermal conductivity; it indicates the rate at which heat passes through a material. The lower the U-value, the better the material is at insulating.

Figure 4.9 presents the cladding systems that have been conceptualized utilizing the Grasshopper modeling tool.



1-Kalzip Profile Sheet
2-Kalzip E clip
3-Thermal Insulation
4-Vapor Control Insulation and Air Sealing Layer
5-Trapezoidal Sheet
6-Lattice Beam

Figure 4-25: Aluminum cladding system details

Each aluminum cladding system is unique, and the specific layers and materials used can vary greatly depending on the project. Figure 4.10 shows the different kalzip systems for flat roof.

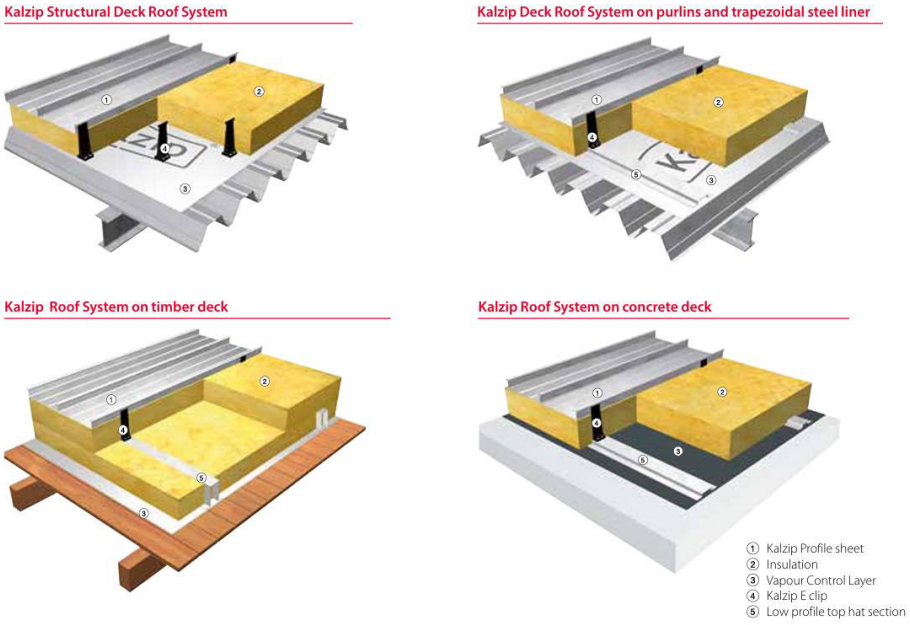


Figure 4-28: Different kalzip systems (Reference: Kalzip Service: Information & Documents)

Figure 4.11 shows the kalzip cladding systems for complex geometrical roofs.



Figure 4-31: kalzip system for complex geometry roof (Reference: Kalzip.com)

The Kalzip profile sheets used in cladding systems are available in standard thicknesses, typically around 0.8 to 1.2, which is recommended for facade cladding when used with rigid thermal insulation or timber lining. This specification ensures that the Kalzip cladding systems can meet various architectural and performance requirements, providing a balance between durability, aesthetics, and environmental considerations (Figure 4.12).
Therefore, stated that the standards in catalog the thickness has been considered between 0.8 to 1.2.

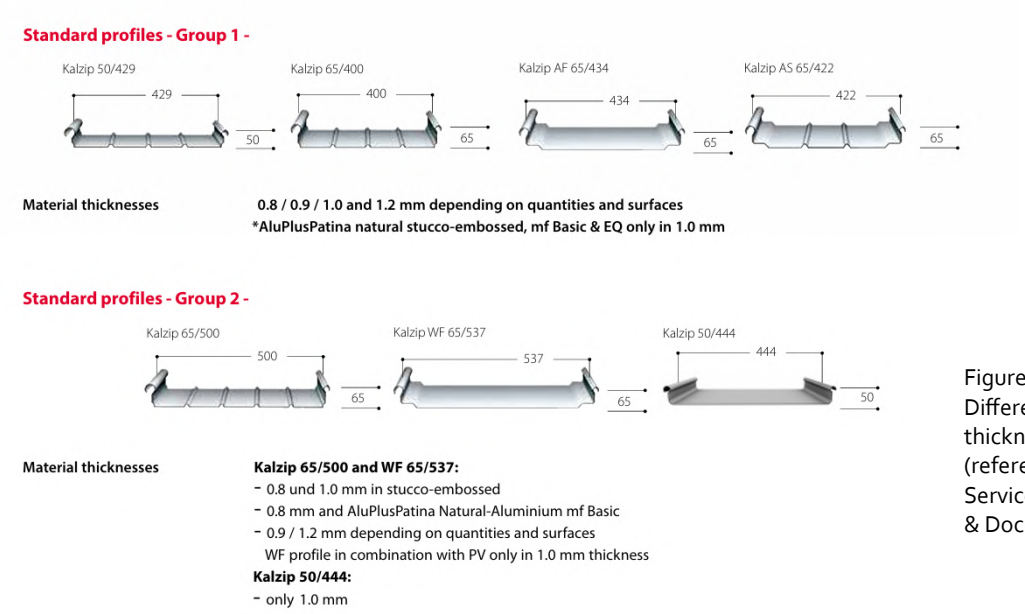


Figure 4-34: Different materials thickness (reference: Kalzip Service: Information & Documents)

4.2.3.2 Modeling Aluminum Cladding system (step1)

In the architectural modeling of the Kalzip aluminum cladding system, specific features were meticulously incorporated, reflecting a comprehensive adherence to the principles outlined in the Environmental Product Declaration as per ISO 14025 and EN 15804+A2. This detailed consideration was guided by a commitment to environmental sustainability and energy efficiency. The system's design parameters were rigorously defined, including a calculated thermal transmittance (U-value) of 0.19 W/m²K, which signifies the system's superior insulation properties and its potential to significantly reduce energy consumption in buildings. Table 4.9 shows the material features.

Material	Thickness	Thermal conductivity	Density
Kalzip profile sheet (Aluminum alloy EN AW-3004,3005, 3105, 6025)	0.8 mm to 1.2 mm	120 w/m.k to 200 w/m.k	2700 kg/m³
XPS, polystyrene Insulation (/EN 12667/ and /EN 13164/ Annex C)	0.1 m to 0.2 m	0.034 W/(mK)	20 - 50 kg/m3
Vapor control layer	0.01 m	-	-
Trapezoidal deck	0.8 mm to 1.2 mm	120 w/m.k to 200 w/m.k	2700 kg/m³

Table 4-25: Materials features of Aluminum cladding system prototype, Appendix D, Page

As illustrated in Table 47, the variables under consideration include the thickness of layers, thermal conductivity, and density. Figure 6 depicts the model as developed in Rhino and Grasshopper (Figure 4.13).

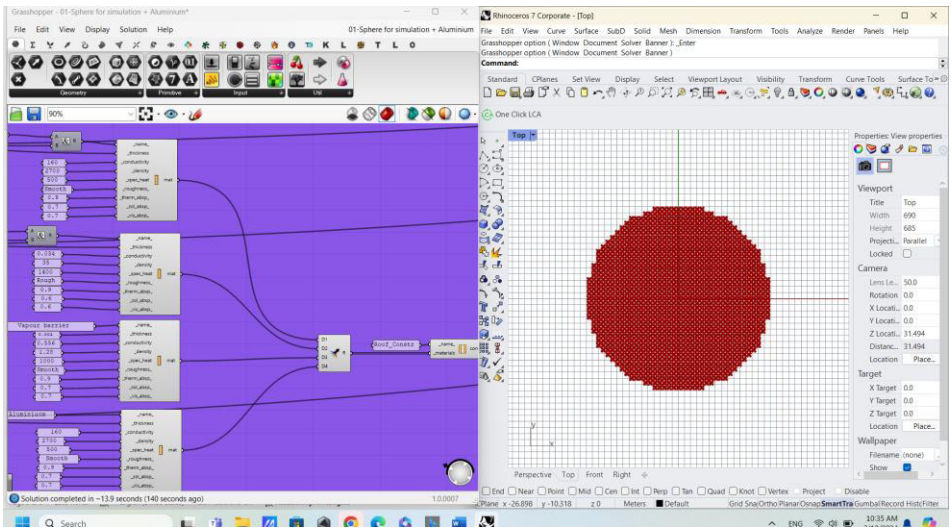


Figure 4-37: Model as developed in Rhino and Grasshopper

4.2.3.3 Climatic analysis in terms of energy usage (Step2)

Table 4.10 presents the foundational data on energy consumption obtained from the parametric modeling of the prototype. The outputs detailed include the cooling and heating requirements, measured in terms of thermal energy per kilowatt-hour, as well as the heating and cooling loads per square meter, DA, cDA, UDI, sDA. These metrics serve as critical inputs for assessing the environmental impact of the prototype during its use phase. The quantified energy demands in cooling and heating provide essential insights into the thermal efficiency of the building's cladding systems, laying the groundwork for a subsequent comprehensive analysis of their environmental footprint. This foundational data is pivotal for evaluating the prototype's performance and will guide the forthcoming assessment of its environmental impact in the use stage.

Table 4-28: final analysis concerning energy consumption, Appendix D Page 459

out:Heating (kWh)	out:Lighting (kWh)	out:Total (kWh)	out:Cooling (kWh/m2)	out:Heating (kWh/m2)	out:Lighting (kWh/m2)	out:Total (kWh/m2)	out:Thermal Load (kWh/m2)	out:Aluminum Ratio %	out:DA	out:cDA	out:UDI	out:UDI low	out:UDI up	out:sDA	out:GA
60917.61	18186.6	83982	6.427819	80.275622	23.965823	110.66926	86.703441	100	0	0	0	0	0	0	100
60915.81	18186.6	83979.47	6.426859	80.273244	23.965823	110.66593	86.700103	100	0	0	0	0	0	0	100
60914.19	18186.6	83977.23	6.426044	80.271117	23.965823	110.66298	86.697161	100	0	0	0	0	0	0	100
60911.5	18186.6	83973.14	6.424197	80.26757	23.965823	110.65759	86.691767	100	0	0	0	0	0	0	100
60910.95	18186.6	83972.04	6.423477	80.266842	23.965823	110.65614	86.690319	100	0	0	0	0	0	0	100
60905.49	18186.6	83956.29	6.409908	80.259646	23.965823	110.63538	86.669554	100	0	0	0	0	0	0	100
60904.65	18186.6	83955.03	6.409354	80.258546	23.965823	110.63372	86.667901	100	0	0	0	0	0	0	100
60901.7	18186.6	83954.14	6.412082	80.254649	23.965823	110.63255	86.666731	100	0	0	0	0	0	0	100
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
46915.67	18186.6	67431.17	3.068963	61.824232	23.965823	88.859018	64.893195	100	0	0	0	0	0	0	100
46914.33	18186.6	67429.27	3.068221	61.82247	23.965823	88.856514	64.890691	100	0	0	0	0	0	0	100
46913.05	18186.6	67427.44	3.067501	61.820782	23.965823	88.854107	64.888283	100	0	0.000091	0	100	0	0	100
46912.48	18186.6	67426.3	3.066734	61.820035	23.965823	88.852592	64.886769	100	0	0	0	0	0	0	100
46911.06	18186.6	67424.28	3.065959	61.818151	23.965823	88.849933	64.88411	100	0	0	0	0	0	0	100
46909.46	18186.6	67417.95	3.059732	61.816047	23.965823	88.841602	64.875779	100	0	0	0	0	0	0	100
46908.18	18186.6	67416.22	3.05913	61.81436	23.965823	88.839313	64.873489	100	0	0.000157	0	100	0	0	100
46906.91	18186.6	67413.88	3.057714	61.81269	23.965823	88.836227	64.870404	100	0	0	0	0	0	0	100
46905.42	18186.6	67411.79	3.056932	61.810728	23.965823	88.833483	64.86766	100	0	0.000041	0	100	0	0	100
46904.56	18186.6	67410.36	3.056175	61.809595	23.965823	88.831593	64.86577	100	0	0	0	0	0	0	100

4.2.3.4 Calculation of the environmental Impacts caused by the annual energy consumption based on kwh in the B6 stage (Step 3)

In this phase of the study, the annual environmental impact attributable to energy consumption for cooling, heating, and lighting systems is quantified. This quantification is achieved by multiplying the total annual energy consumption, measured in kilowatt-hours, by the environmental impact coefficient associated with the generation, transmission, and distribution of one kilowatt-hour of electricity in Boston. It is important to note that in this stage, in addition to environmental impacts, other factors such as Daylight Autonomy (DA), Continuous Daylight Autonomy (cDA), and Useful Daylight Illuminance (UDI) are also considered. These parameters introduce complexity to the decision-making process, ensuring that the selection of the optimized model is grounded in a multifaceted approach that encapsulates both environmental and performance-based objectives (Table4.11,4.12).

in:trapezoidal sheeting aluminum	in:XPS Extruded Polystyrene	in:Corrugated sheet Aluminium	out:Cooling (kWh)	out:Heating (kWh)	out:Lighting (kWh)	out:Total (kWh)	out: DA	out: cDA	out: UDI	out: UDI low	out: UDI up	out: sDA	out: GA	Acidification	Carcinogenics	Ecotoxicity	Eutrophication	Fossil fuel depletion	Global warming	Non carcinogenics	Ozone depletion	Respiratory effects	Smog
0.0012	0.2	0.0012	2319.2	46905	18187	67410	0	0	0	0	0	0	100	27.7	0.0001	13527.7	9.03	33546	15723	0	0	3.34	345
0.0011	0.2	0.0012	2319.8	46905	18187	67412	0	0	0	100	0	0	100	27.7	0.0001	13528	9.03	33546	15723	0	0	3.34	345
0.001	0.2	0.0012	2320.4	46907	18187	67414	0	0	0	0	0	0	100	27.7	0.0001	13528.4	9.03	33548	15724	0	0	3.34	345
0.0009	0.2	0.0012	2321.4	46908	18187	67416	0	0	0	100	0	0	100	27.7	0.0001	13528.9	9.03	33549	15724	0	0	3.34	345
0.0008	0.2	0.0012	2321.9	46909	18187	67418	0	0	0	0	0	0	100	27.7	0.0001	13529.2	9.03	33550	15725	0	0	3.34	345
0.0012	0.2	0.0011	2326.6	46911	18187	67424	0	0	0	0	0	0	100	27.7	0.0001	13530.5	9.03	33553	15726	0	0	3.34	345
0.0011	0.2	0.0011	2327.2	46912	18187	67426	0	0	0	0	0	0	100	27.7	0.0001	13530.9	9.03	33554	15727	0	0	3.34	345
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
0.0011	0.1	0.001	4859.3	60899	18187	83945	0	0	0	0	0	0	100	34.5	0.0001	16845.7	11.2	41774	19579	0	0	4.15	429
0.0009	0.1	0.001	4860.6	60898	18187	83946	0	0	0	0	0	0	100	34.5	0.0001	16846	11.2	41774	19580	0	0	4.15	429
0.001	0.1	0.001	4859.9	60899	18187	83946	0	0	0	0	0	0	100	34.5	0.0001	16846	11.2	41774	19580	0	0	4.15	429
0.0008	0.1	0.001	4860.8	60900	18187	83947	0	0	0	0	0	0	100	34.5	0.0001	16846.3	11.2	41775	19580	0	0	4.15	429
0.001	0.1	0.0009	4864.8	60901	18187	83953	0	0	0	0	0	0	100	34.5	0.0001	16847.4	11.2	41778	19581	0	0	4.15	429
0.0009	0.1	0.0009	4865.5	60901	18187	83953	0	0	0	0	0	0	100	34.5	0.0001	16847.5	11.2	41778	19581	0	0	4.15	429
0.0008	0.1	0.0009	4865.8	60902	18187	83954	0	0	0	0	0	0	100	34.5	0.0001	16847.7	11.2	41779	19582	0	0	4.15	429
0.0012	0.1	0.0009	4863.8	60905	18187	83955	0	0	0	0	0	0	100	34.6	0.0001	16847.9	11.2	41779	19582	0	0	4.15	429
0.0011	0.1	0.0009	4864.2	60905	18187	83956	0	0	0	0	0	0	100	34.6	0.0001	16848.1	11.2	41780	19582	0	0	4.15	429
0.0012	0.1	0.0008	4874.5	60911	18187	83972	0	0	0	0	0	0	100	34.6	0.0001	16851.3	11.2	41787	19586	0	0	4.15	429
0.0011	0.1	0.0008	4875	60912	18187	83973	0	0	0	0	0	0	100	34.6	0.0001	16851.5	11.2	41788	19586	0	0	4.15	429
0.001	0.1	0.0008	4876.4	60914	18187	83977	0	0	0	0	0	0	100	34.6	0.0001	16852.3	11.2	41790	19587	0	0	4.15	429
0.0009	0.1	0.0008	4877.1	60916	18187	83979	0	0	0	0	0	0	100	34.6	0.0001	16852.8	11.2	41791	19587	0	0	4.15	429
0.0008	0.1	0.0008	4877.8	60918	18187	83982	0	0	0	0	0	0	100	34.6	0.0001	16853.3	11.2	41792	19588	0	0	4.16	430

Table 4-31: environmental effects caused by the annual energy consumption base on kwh in the B6 stage, Appendix D, Page 460

in:XPS Extruded Polystyrene	in:Corrugated sheet Aluminiuom	out:Cooling (kWh/m2)	out:Heating (kWh/m2)	out:Lighting (kWh/m2)	out:Total (kWh/m2)	out:Thermal Load (kWh/m2)	Acidification	Carcinogenics	Ecotoxicity	Eutrophication	Fossil fuel depletion	Global warming	Non carcinogenics	Ozone depletion	Respiratory effects	Smog
0.2	0.0012	3.056175	61.8096	23.96582	88.83159	64.86577	0.026694405	1.15195E-07	13.01707487	0.008689224	32.27950645	15.1293243	5.0934E-07	1.8905E-06	0.0032093	0.3317415
0.2	0.0012	3.056932	61.81073	23.96582	88.83348	64.86766	0.026695183	1.15198E-07	13.01745415	0.008689477	32.28044698	15.12976513	5.0936E-07	1.8906E-06	0.0032093	0.3317512
0.2	0.0012	3.057714	61.81269	23.96582	88.83623	64.870404	0.026696312	1.15203E-07	13.01800481	0.008689845	32.28181249	15.13040514	5.0938E-07	1.8906E-06	0.0032095	0.3317652
0.2	0.0012	3.05913	61.81436	23.96582	88.83931	64.873489	0.026697582	1.15209E-07	13.0186239	0.008690258	32.2833477	15.13112469	5.094E-07	1.8907E-06	0.0032096	0.331781
0.2	0.0012	3.059732	61.81605	23.96582	88.8416	64.875779	0.026698524	1.15213E-07	13.01908345	0.008690565	32.28448728	15.13165881	5.0942E-07	1.8908E-06	0.0032097	0.3317927
0.2	0.0011	3.065959	61.81815	23.96582	88.84993	64.88411	0.026701952	1.15228E-07	13.02075529	0.008691681	32.28863308	15.13360193	5.0949E-07	1.891E-06	0.0032102	0.3318353
0.2	0.0011	3.066734	61.82004	23.96582	88.85259	64.886769	0.026703047	1.15232E-07	13.02128889	0.008692037	32.2899563	15.13422212	5.0951E-07	1.8911E-06	0.0032103	0.3318489
0.2	0.0011	3.067501	61.82078	23.96582	88.85411	64.888283	0.02670367	1.15235E-07	13.02159272	0.00869224	32.29070972	15.13457525	5.0952E-07	1.8912E-06	0.0032104	0.3318567
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
0.1	0.001	6.403498	80.25056	23.96582	110.6199	86.65406	0.035661005	1.53889E-07	17.38948581	0.011607918	43.12213188	20.21123585	6.8043E-07	2.5255E-06	0.0042872	0.4431729
0.1	0.001	6.405109	80.2503	23.96582	110.6212	86.655412	0.035661562	1.53891E-07	17.38975713	0.011608099	43.12280469	20.21155119	6.8044E-07	2.5256E-06	0.0042873	0.4431798
0.1	0.001	6.404314	80.25123	23.96582	110.6214	86.655541	0.035661615	1.53892E-07	17.38978301	0.011608116	43.12286888	20.21158128	6.8044E-07	2.5256E-06	0.0042873	0.4431804
0.1	0.001	6.405445	80.25199	23.96582	110.6233	86.657437	0.035662395	1.53895E-07	17.3901635	0.01160837	43.1238124	20.2120235	6.8046E-07	2.5256E-06	0.0042874	0.4431901
0.1	0.0009	6.41068	80.25422	23.96582	110.6307	86.664895	0.035665464	1.53908E-07	17.39166015	0.011609369	43.12752376	20.21376301	6.8052E-07	2.5258E-06	0.0042878	0.4432283
0.1	0.0009	6.411588	80.25371	23.96582	110.6311	86.665295	0.035665629	1.53909E-07	17.39174042	0.011609423	43.12772282	20.21385631	6.8052E-07	2.5258E-06	0.0042878	0.4432303
0.1	0.0009	6.412082	80.25465	23.96582	110.6326	86.666731	0.03566622	1.53911E-07	17.39202859	0.011609615	43.12843742	20.21419124	6.8053E-07	2.5259E-06	0.0042879	0.4432377
0.1	0.0009	6.409354	80.25855	23.96582	110.6337	86.667901	0.035666701	1.53914E-07	17.39226338	0.011609772	43.12901965	20.21446413	6.8054E-07	2.5259E-06	0.0042879	0.4432437
0.1	0.0009	6.409908	80.25965	23.96582	110.6354	86.669554	0.035667382	1.53916E-07	17.3925951	0.011609993	43.12984225	20.21484968	6.8055E-07	2.526E-06	0.004288	0.4432521
0.1	0.0008	6.423477	80.26684	23.96582	110.6561	86.690319	0.035675927	1.53953E-07	17.39676216	0.011612775	43.14017565	20.21969292	6.8071E-07	2.5266E-06	0.004289	0.4433583
0.1	0.0008	6.424197	80.26757	23.96582	110.6576	86.691767	0.035676523	1.53956E-07	17.39705274	0.011612969	43.14089622	20.22003065	6.8073E-07	2.5266E-06	0.0042891	0.4433657
0.1	0.0008	6.426044	80.27112	23.96582	110.663	86.697161	0.035678743	1.53965E-07	17.39813519	0.011613692	43.14358047	20.22128875	6.8077E-07	2.5268E-06	0.0042894	0.4433933
0.1	0.0008	6.426859	80.27324	23.96582	110.6659	86.700103	0.035679953	1.53971E-07	17.39872559	0.011614086	43.14504451	20.22197494	6.8079E-07	2.5269E-06	0.0042895	0.4434083
0.1	0.0008	6.427819	80.27562	23.96582	110.6693	86.703441	0.035681327	1.53977E-07	17.39939545	0.011614533	43.14670562	20.2227535	6.8082E-07	2.527E-06	0.0042897	0.4434254

Table 4-34: environmental impacts caused by the annual energy consumption per m2 in the B6 stage, Appendix D, Page 460

4.2.3.5 Discussion and primarily Analysis

To compare the role of the B6 stage in contributing to global warming, acidification, and fossil fuel depletion, the environmental impact attributable to a sphere with an area of 1519.5929 m² was assessed. This was achieved by multiplying the impact per unit area by the total surface area of the sphere. Subsequently, to align with the lifespan

defined in Environmental Product Declarations (EPD), which typically extends to 50 years, the results were extrapolated over this period. Table 4.13 delineates the contributions of each lifecycle stage to global warming, acidification, and fossil fuel depletion, thereby facilitating a nuanced understanding of their environmental implications. Diagram 4.30 shows a visualization of table 4.13.

Table 4-37: environmental Impact caused by Aluminum cladding system, Appendix D, Page 461

Parameter	Unit	A1-A3	A5	B6	C1	C2	C3	C4	D
GWP-total	kg CO2 eq	3.14E+00	4.84E-02	9.70E+01	1.41E-04	1.15E-02	4.20E-01	1.58E-02	-6.86E-01
ODP	kg CFC11 eq	3.99E-01	4.04E-08	9.96E+01	1.15E-08	9.23E-09	8.82E-07	3.02E-07	5.01E-05
AP	mol H+ eq	9.39E+00	4.14E-03	9.21E+01	1.12E-04	2.18E-02	8.35E-02	5.99E-02	-1.70E+00

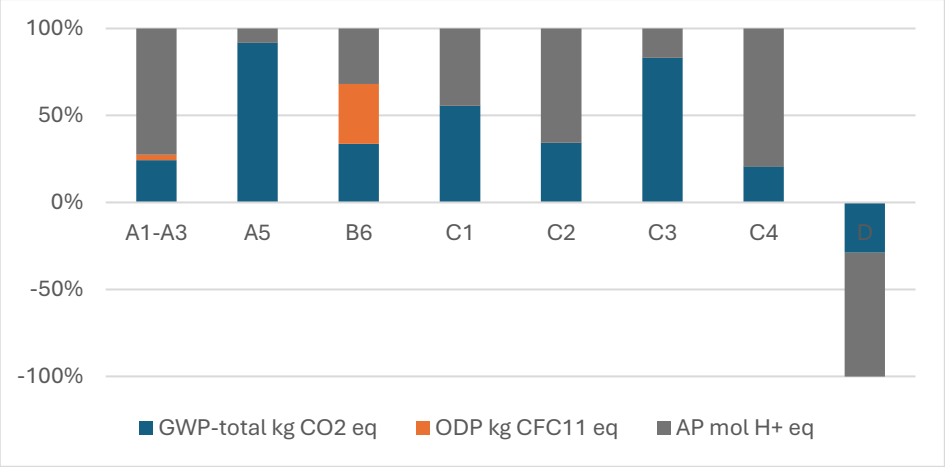


Diagram 4-30: Visualization of table 4-13, Appendix C, Page 432

Analyzing all environmental impacts at the B6 stage, it becomes evident that aluminum cladding contributes notably to global warming and acidification, with a lesser but still present effect on ozone depletion. The predominance of GWP and AP in the B6 stage indicates that these are areas where architects can make significant environmental improvements through material selection and design considerations.

In an evaluation of the environmental impact of an aluminum cladding system encompassing a 50-year lifespan, the B6 stage—characterized by energy consumption in heating, cooling, and lighting—emerges as a phase of considerable ecological significance. Specifically, the Global Warming Potential (GWP) of the B6 stage is markedly predominant, with a staggering 1,150,000 kg of CO_2 equivalent, surpassing the A1-A3 stages by 96.77%, which points to the immense role of operational energy in contributing to a building's carbon footprint. The acidification potential (AP), at 2,030 mol H+ eq, further accentuates B6's impact, dwarfing the A1-A3 stages by 89.80%, highlighting the substantial emissions of acidifying pollutants during the building's operational phase. Conversely, the Ozone Depletion Potential (ODP) remains relatively nominal at 0.144 kg of CFC11 equivalent, though it still represents an important impact category. Given that the examined building is roofed with 1519.5929 m^2 of aluminum cladding, the data profoundly illustrates the B6 stage's environmental ramifications due to energy use. Consequently, it becomes imperative for architects to conscientiously address material selection and energy-efficient design strategies during the initial design phase, aiming to mitigate the environmental impacts that are significantly amplified during the building's operational lifetime.

Since the sole assessment of environmental impact is insufficient to evaluate a building's sustainability credentials, the researcher expanded the analysis to include variables such as Daylight Autonomy (DA), Continuous Daylight Autonomy (cDA), Useful Daylight Illuminance (UDI), and Spatial Daylight Autonomy (sDA), in addition to thermal load considerations. The results indicated that an aluminum cladding system, when used as a single cladding solution, is not the optimal choice due to its limited access to natural daylight. Consequently, a comprehensive analysis of polycarbonate materials was undertaken to explore their potential in enhancing the building's sustainability profile. This examination aimed to ascertain the efficacy of polycarbonate as an alternative cladding material, considering its light transmission capabilities and thermal performance.

4.2.4 Polycarbonate Cladding System

4.2.4.1 A Review of Polycarbonate

A polycarbonate cladding system is a building envelope solution that utilizes polycarbonate panels as the exterior facing material. These panels can be solid, multi-walled, or incorporate other structural configurations for tailored performance. Polycarbonate cladding systems have emerged as a significant innovation in the field of architectural design, merging unparalleled durability, optimal light transmission, and aesthetic versatility. These systems are constructed from polycarbonate, a distinguished thermoplastic material celebrated for its remarkable strength and clarity, thereby revolutionizing architectural methodologies concerning building envelopes. This revolution has facilitated the development of energy-efficient and visually appealing structures, significantly impacting contemporary architecture (Bagotia, Choudhary, and Sharma 2018).

The allure of polycarbonate cladding primarily derives from its capability to diffuse natural light while simultaneously offering insulation. This dual functionality significantly diminishes energy demands associated with lighting and climate regulation within buildings, presenting a sustainable approach to architectural design (Wong 2017). Polycarbonate's inherent impact resistance and lightweight properties empower architects to pursue innovative design solutions. This includes the creation of seamless exteriors, complex roofing systems, and other elements that enhance both the aesthetic appeal and functional performance of contemporary buildings. Additionally, transparent systems, such as windows, façades, skylights, and arcades, play a pivotal role in building design. Their characteristics – thermal and solar transmittance, transparency, size, and orientation – significantly influence a building's energy consumption (Zahra Benaddi, Boukhattem, and Cesar Tabares-Velasco 2024) (Higgins and Brittain 2005)(Oral, Yener, and Bayazit 2004b). Polycarbonate's suitability for sustainable building design stems from its combination of advantageous physical properties. This thermoplastic polymer's versatility in thickness (ranging from approximately 25mm to over 35mm in cladding systems) allows for significant design adaptability. Architects can manipulate light transmission and thermal insulation characteristics to align with specific project goals and sustainability objectives (Kamal 2020).

The thermal transmittance, or U-value, of polycarbonate significantly highlights its efficiency in insulating structures, thereby promoting energy conservation by minimizing heating and cooling necessities(Dolui and Agrawal 2024; Mohammed,

Menkabo, and Budaiwi 2023). Furthermore, the exceptional light transmission capacity of polycarbonate, capable of permitting up to 90% of natural light, not only augments the aesthetic appeal of constructions by incorporating natural lighting but also fosters energy savings (Mazin M. Menkabo et al. 2024). In terms of durability, polycarbonate's high impact resistance outperforms traditional glazing materials like glass, ensuring both longevity and safety across various applications, from external cladding to security measures. This flexibility allows it to be molded into numerous shapes without compromising on impact resistance, affording architects and designers with creative liberties in their projects (Davidson et al. 2024). However, the thermal expansion coefficient of polycarbonate is comparatively higher than other building materials, necessitating meticulous installation procedures to allow for expansion and contraction without affecting the structural integrity. Despite this, its overall performance metrics, including durability, thermal insulation, light transmission, impact resistance, and design flexibility, position polycarbonate as a highly esteemed material in contemporary architectural practices(Moretti, Zinzi, and Belloni 2014).

The main characteristics of polycarbonate, which underscore its environmental friendliness, include its high resistance to weathering and aging (ensuring long-term performance), the ability to allow natural light penetration (reducing artificial lighting needs), effective thermal insulation (enhancing energy efficiency), and impact resistance (guaranteeing safety and structural longevity). Additionally, its design versatility, lightweight nature, UV resistance, and the environmental considerations associated with its production, such as the use of bisphenol A, underline the material's complex but beneficial role in sustainable architecture (Maraveas 2019). Fig 4.14 & 4.15 shows an example of polycarbonate cladding system implemented on spatial structure domes.



Figure 4-40: Jewel Changi Airport | Safdie Architects (Reference: https://constructiondatabase.org `



Figure 4-43: The Shed. Diller Scofidio + Renfro and collaborating architect Rockwell's (Referens: https://www.archdaily.com)

Table 4.14 succinctly outlines the advantages and a key consideration regarding the environmental impact of polycarbonate cladding systems, highlighting their role in modern sustainable architecture.

Feature	Description
Durability	High resistance to weathering and aging, maintaining performance over time.
Light Transmission	Allows natural light to penetrate through, reducing the need for artificial lighting.
Thermal Insulation	Provides a barrier to heat transfer, contributing to energy efficiency in buildings.
Impact Resistance	Resists breakage from impact, ensuring safety and longevity of the structure.
Aesthetic Flexibility	Offers design versatility with options for colors, textures, and forms.
Weight	Lightweight material eases handling and installation, reducing structural support requirements.
UV Resistance	Can be treated with coatings to resist UV degradation and prevent yellowing.
Environmental Impact	Production involves chemicals like bisphenol A, raising concerns about health and sustainability.

Table 4-40: Environmental advantages of Polycarbonate

Polycarbonate cladding systems, while offering numerous advantages in terms of light transmission, flexibility, and impact resistance, are not without their limitations. A comprehensive understanding of these drawbacks is essential for architects and builders to make informed decisions and implement effective mitigation strategies. Flammability is a notable concern with polycarbonate materials. Despite possessing inherent fire resistance, polycarbonates are combustible and can contribute to flame spread and smoke production in the event of a fire. This characteristic necessitates a judicious approach to building design, often requiring the integration of additional fire-retardant coatings or treatments to enhance safety(Arumugam et al. 2024).

UV Degradation presents another significant challenge. Extended exposure to ultraviolet light can lead to the yellowing of polycarbonate and a reduction in its material strength, compromising both aesthetic appeal and structural integrity. The

application of UV-resistant coatings or the use of specially formulated grades of polycarbonate designed for prolonged outdoor use is frequently employed to counteract these effects (Ainali, Bikiaris, and Lambropoulou 2024)(Kuyyakanont and Iwata 2024). The Susceptibility to Scratching and Abrasion of polycarbonate, due to its softer composition compared to glass, affects its visual clarity and can diminish light transmission and visibility in specific applications. This limitation primarily impacts the material's appearance, though severe abrasion can affect functional aspects as well(Moro 2024). Environmental Concerns associated with the production and disposal of polycarbonate include its energy-intensive manufacturing process and the use of potentially harmful chemicals. The challenges related to the disposal and recycling of polycarbonate materials have prompted a shift towards the incorporation of recycled content and the exploration of more sustainable manufacturing practices (Martínez-Narro, Hassan, and Phan 2024)(Kolluru et al. 2024). Vapor Transmission rates of polycarbonate can be higher than those of other cladding materials. In certain environmental conditions or architectural configurations, this may necessitate the installation of additional vapor barriers to mitigate moisture-related issues within the wall system (Mazin M. Menkabo et al. 2024)(Kolluru et al. 2024). The relative importance of these drawbacks varies depending on specific project requirements, geographic location, and budget constraints. However, many of these challenges can be mitigated through careful material selection, such as opting for UV-resistant grades or incorporating flame-retardant additives, and by employing proper installation techniques. Ongoing advances in technology are focused on enhancing fire performance, environmental sustainability, and scratch resistance of polycarbonate systems. Through research and development, the goal is to address these limitations, improving the overall utility and application of polycarbonate cladding systems in contemporary architectural designs. Improving the quality of polycarbonate involves enhancing its inherent properties and addressing any limitations to expand its application range and effectiveness, especially in the construction and architectural sectors. Table 4.15 categories highlight key areas for improvement:

Property	Description	Improvement Strategies
UV Stabilization and Protection	Prolonged exposure to UV radiation can cause polycarbonate to yellow and degrade over time.	Incorporating UV stabilizers or protective coatings to significantly reduces UV degradation, extending the material's lifespan and maintaining its clarity.
Thermal Insulation	While polycarbonate has good thermal insulation properties, there is room for improvement in various climates.	Developing multiwall polycarbonate sheets with additional air pockets or incorporating insulating materials like aerogels to enhance thermal performance, reducing energy consumption for heating and cooling.
Impact Resistance	Polycarbonate is known for its high impact resistance, but greater resistance may be beneficial in certain applications.	Reinforcing polycarbonate with fibers or nanocomposites to further increases its impact resistance, making it suitable for more demanding applications like ballistic protection.
Scratch Resistance	The surface of polycarbonate can be prone to scratching, affecting its aesthetic and optical properties.	Applying hard coatings or developing composite materials with enhanced surface hardness to improve scratch resistance, preserving the material's appearance and functionality.
Fire Resistance	Enhancing the fire resistance of polycarbonate is crucial for its application in safety-critical areas.	Incorporating fire retardant additives or developing composite materials that better resist ignition and slow the spread of flames to improve safety.

Sustainability	The production of polycarbonate typically involves petroleum-based resources and can generate waste.	Researching bio-based polycarbonate alternatives and recycling technologies to improve its environmental footprint, making polycarbonate a more sustainable choice.
Chemical Resistance	Polycarbonate may be susceptible to damage or degradation when exposed to certain chemicals.	Enhancing the chemical resistance of polycarbonate through material modification or protective coatings to broaden its application in industrial environments.
Color Stability	Maintaining color stability under various environmental conditions is essential for aesthetic applications.	Developing advanced colorants and stabilizers that resist fading and maintain color integrity over time to enhance the aesthetic appeal of polycarbonate products.

Table 4-43: key areas for improvement poly carbonate features

Recognizing the crucial role of U-values in material performance and energy efficiency, the researcher in this study conducted research to identify innovative strategies for improving the U-value of polycarbonate. Table 4.16 summarizes the innovative strategies developed to improve the thermal insulation feature of polycarbonate cladding systems, highlighting their importance in enhancing energy efficiency and sustainability in building designs.

Strategy	Description	Innovation
Multiwall Structures	Multiwall polycarbonate sheets consist of multiple layers separated by vertical ribs, creating air pockets that enhance insulation.	Development of sheets with more layers and optimized air pocket design to minimize heat transfer, significantly improving thermal insulation without compromising light transmission.
Aerogel Integration	Aerogels are highly porous, lightweight materials known for their exceptional thermal insulating properties.	Embedding aerogel within polycarbonate sheets or panels to drastically reduces heat transfer, offering superior insulation with minimal thickness increase.
Nanotechnology	Nanotechnology involves manipulating materials at the atomic or molecular scale to achieve superior properties.	Incorporating nano-insulating materials into polycarbonate panels to reduce thermal conductivity and enhance insulation efficiency without affecting transparency.
Phase Change Materials (PCMs)	PCMs absorb or release heat during phase transitions, effectively storing thermal energy.	Integrating PCMs into polycarbonate cladding systems to act as thermal buffers, absorbing excess heat during the day and releasing it at night, thereby stabilizing indoor temperatures.
Infrared Reflective Coatings	Certain coatings can reflect infrared radiation, reducing heat transfer through the material.	Applying infrared-reflective coatings to the surface of polycarbonate sheets to reflect heat while allowing visible light to pass through, enhancing thermal insulation without affecting natural lighting.
Improved Sealing Techniques	Gaps and leaks in cladding systems can significantly impact thermal insulation.	Developing advanced sealing and joint systems that minimize air leaks in multiwall polycarbonate

		installations, ensuring better overall thermal performance.
Hybrid Systems	Combining polycarbonate with other materials to leverage their insulating properties.	Creating hybrid cladding systems that combine polycarbonate with materials like insulated metal panels or foam insulation, offering enhanced thermal performance and structural stability.
Smart Glazing Technologies	Smart glazing involves materials or coatings that can change their properties in response to environmental conditions.	Implementing smart glazing solutions that adjust the thermal and light transmission properties of polycarbonate cladding in response to temperature changes, optimizing energy use and comfort levels.

Table 4-46: different strategies to improve U-values of polycarbonate, (refrerenc:(VELUX Group 2024)(Grayevsky 2023)(Moslan et al. 2021))

One of the most renowned polycarbonate cladding systems utilizes multiwall structures, a choice that is favored for several compelling reasons. Multiwall polycarbonate is a type of thermoplastic that is lightweight, yet possesses remarkable strength and durability, which makes it an ideal material for cladding purposes. The multiwall design, characterized by its multiple layers separated by vertical ribs, offers superior thermal insulation compared to single-layered materials.

This design not only enhances energy efficiency by reducing heat loss during colder months and heat gain during warmer months but also contributes to significant cost savings in heating and cooling expenses over time. Additionally, multiwall polycarbonate panels allow for a high level of light transmission while providing protection against harmful UV radiation, making them a preferred choice for creating bright, naturally lit environments without compromising on occupant comfort and protection. Furthermore, the versatility and ease of installation of multiwall polycarbonate systems enable architects and builders to explore innovative architectural designs, offering both aesthetic appeal and functional benefits. Figure 50 illustrates the multiwall structures, along with detailed information regarding their installation on roofs and an example of polycarbonate cladding system implemented on spatial structure domes. Figure 4-46 shows a sample of Multiwall structure polycarbonate panel& installation details.

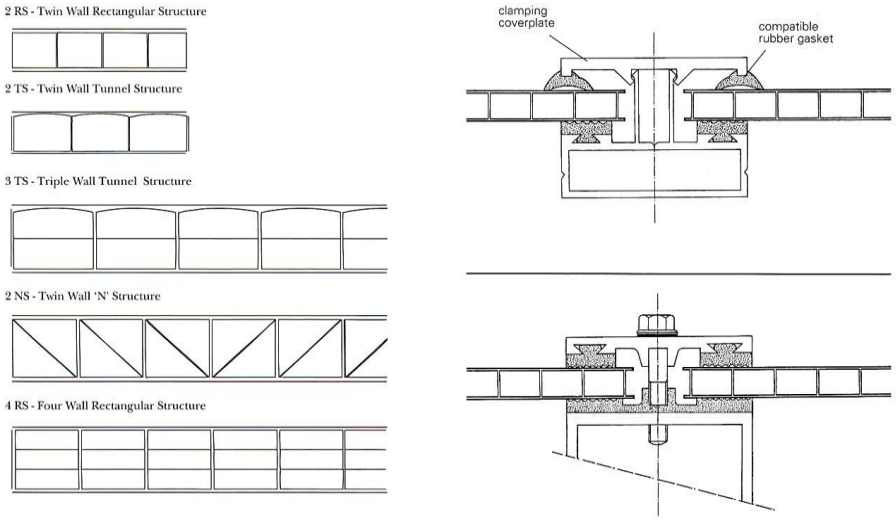


Figure 4-47: Multiwall structure polycarbonate panel& installation details(Reference : Dr Dianat,2017)

4.2.4.2 Modeling polycarbonate cladding system (Step 1)

The primary material chosen for analysis within this investigation is polycarbonate. This examination initiates with the adoption of multiwall polycarbonate systems aimed at augmenting the U-value, thereby elevating the energy efficiency of buildings. Polycarbonate sheets are meticulously engineered with stratified layers, delineated by vertical ribs, which form air cavities instrumental in enhancing thermal insulation. This architectural configuration is critical for the regulation of internal temperatures, facilitating the retention of heat during cooler periods and the dissipation of heat in warmer intervals. Table 4-17 elucidates the characteristics of polycarbonate materials, providing a thorough exposition of their intrinsic properties.

This attribute significantly contributes to the overarching goal of optimizing energy efficiency in constructed environments. The analysis proceeded with the employment of Grasshopper to model these systems, selecting a sphere as the optimized geometry based on prior phases. The initial scenario concentrated on the application of Multiwall Polycarbonate Sheets for cladding purposes.

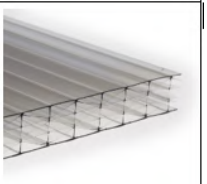
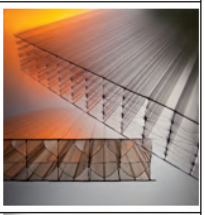
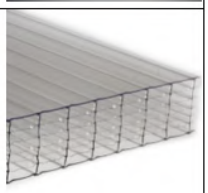
Thickness (mm)	Product	Light Transmission	U-Value (W/m2 K)	Nominal Sheet Weight (kg/m2)	Standard Sheet Sizes	Panels
25	Clear (PC25-C)	62%	1.4	3.1	Maximum Width: 2100mm Standard Max Length: 7m (and CTS)	
	Bronze (PC25-B)	11%				
	Opal (PC25-O)	28%				
	Bronze/Opal (PC25-B/O)	8%				
	Solar guard (PC25-SG)	7%	1.6	3.4		
32	Clear (PC32-C)	64%	1.25	3.6	Maximum Width: 2100mm Standard Max Length: 7m (and CTS)	
	Bronze (PC32-B)	7%				
	Opal (PC32-O)	33%				
	Bronze/Opal (PC32-B/O)	7%				
	Solar guard (PC32-SG)	4%	1.25	3.4		
35	Clear (PC35-C)	63%	1.2	3.9	Maximum Width: 2100mm Standard Max Length: 7m (and CTS)	
	Bronze (PC35-B)	7%				
	Opal (PC35-O)	33%				
	Bronze/Opal (PC35-B/O)	7%				
	Solar guard (PC35-SG)	4%	1.2	3.4		

Table 4-49: Physical feature of polycarbonate, Appendix D, Page 461

To ensure the fidelity of polycarbonate characteristic modeling, and in compliance with Massachusetts state regulations mandating the use of materials with an Environmental Product Declaration (EPD), an exhaustive review was conducted across several EPD databases (IBU, The International EPD® System, Sustainable Minds Transparency Catalog, ecomedes, BuildingGreen).
The architectural modeling was conducted using Rhino, incorporating the Grasshopper plugin to facilitate complex, parametric designs (Figure 4.17).

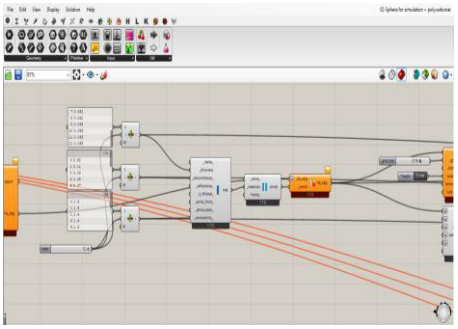


Figure 4-50: Modeling in Grasshopper,(Reference: Author, ABITAlab

4.2.4.3 Climatic analysis in terms of energy usage (Step2)

The characterization of climatic features was conducted in accordance with the standards established by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), ensuring the precise integration of environmental parameters within the analytical model. Advanced environmental simulations were facilitated through the use of Honeybee and Ladybug plugins, which are instrumental

in conducting detailed climatic analyses. Regarding polycarbonate materials, critical variables such as thickness, light transmission, and U-value were meticulously examined. The analysis yielded outcomes including cooling, heating, thermal load, Daylight Autonomy (DA), Continuous Daylight Autonomy (cDA), Useful Daylight Illuminance (UDI), and Spatial Daylight Autonomy (sDA). The subsequent table provides an elucidation of the polycarbonate model's analysis outputs (Table 4.18).

out:Transmittance	out:Conductivity	out:Thermal Load (kWh)	out:Cooling (kWh)	out:Heating (kWh)	out:Lighting (kWh)	out:Total (kWh)	out:Cooling (kWh/m2)	out:Heating (kWh/m2)	out:Lighting (kWh/m2)	out:Total (kWh/m2)	out:Thermal Load (kWh/m2)	out:DA	out:cDA	out:UDI	out:UDI low	out:UDI up	out:sDA
0.62	1.4	338173	83992.3	254181	6150.06	344324	110.6829	334.9532	8.10439	453.7405	445.6361	94.47	94.5301	3.16857	5.45005	91.3797	1
0.11	1.4	338105	66490.8	271614	6150.06	344255	87.61987	357.92633	8.10439	453.6506	445.5462	94.47	94.5302	3.16853	5.45005	91.3799	1
0.28	1.4	338182	73623.5	264559	6150.06	344332	97.01909	348.62867	8.10439	453.7521	445.6478	94.47	94.5303	3.16824	5.45	91.3801	1
0.08	1.4	338125	65200.9	272924	6150.06	344275	85.92005	359.65265	8.10439	453.6771	445.5727	94.47	94.5302	3.17011	5.45	91.3781	1
0.07	1.6	340143	64327.9	275815	6150.06	346293	84.76961	363.46186	8.10439	456.3359	448.2315	94.47	94.5302	3.16847	5.45003	91.3798	1
0.64	1.25	331974	86019.2	245955	6150.06	338124	113.3538	324.11256	8.10439	445.5707	437.4663	94.47	94.5302	3.17005	5.45	91.3784	1
0.07	1.25	332111	66801.7	265309	6150.06	338261	88.02954	349.61732	8.10439	445.7512	437.6469	94.47	94.5302	3.17031	5.45	91.378	1
0.33	1.25	332002	77270	254732	6150.06	338152	101.8243	335.67962	8.10439	445.6083	437.5039	94.4699	94.5302	3.16912	5.45003	91.3791	1
0.04	1.25	332995	66408.2	266587	6150.06	339145	87.51102	351.30097	8.10439	446.9164	438.812	94.47	94.5302	3.16928	5.45	91.379	1
0.63	1.2	329193	86561.7	242631	6150.06	335343	114.0687	319.73331	8.10439	441.9064	433.802	94.47	94.5302	3.17013	5.45003	91.3783	1
0.07	1.2	330195	68421.2	261774	6150.06	336346	90.1637	344.95919	8.10439	443.2273	435.1229	94.47	94.5302	3.16873	5.45003	91.3797	1
0.33	1.2	329251	78049.6	251202	6150.06	335401	102.8518	331.02671	8.10439	441.9829	433.8785	94.47	94.5302	3.17162	5.45	91.3768	1
0.04	1.2	330295	67210.5	263085	6150.06	336445	88.56818	346.6859	8.10439	443.3585	435.2541	94.47	94.5302	3.16793	5.45	91.3802	1

Table 4-52: output analysis of polycarbonate, Appendix D, Page 462

4.2.4.4 Calculation of the environmental Impacts caused by the annual energy consumption based on kWh in the B6 stage (Step 3)

The foundation of the environmental assessments and analyses within this project is anchored in the B6 stage, specifically focusing on the operational period. The criteria for measuring environmental impact are primarily based on the energy consumption required for cooling, heating, and lighting. Given that the energy provider in Boston for both cooling and heating systems relies on electricity, the "market for electricity, low voltage was modeled using openLCA. Subsequently, the environmental impacts, as quantified by this model, were meticulously calculated. It is important to note that all related processes and results have been comprehensively addressed in section one of this study (Table 4.19).

Impact category	Reference unit	Result
Acidification	kg SO_2 eq	0.000411533
Carcinogenic	CTUh	1.7759E-09
Ecotoxicity	CTUe	0.200677104
Eutrophication	kg N eq	0.000133957
Fossil fuel depletion	MJ surplus	0.497635447
Global warming	kg CO_2 eq	0.233240495
Non carcinogenic	CTUh	7.85226E-09
Ozone depletion	kg CFC-11 eq	2.91448E-08
Respiratory effects	kg PM2.5 eq	4.94753E-05
Smog	kg O_3 eq	0.005114277

Table 4-55: Environmental Impact of Producing and Transmitting 1 kWh of Low-Voltage Electricity in Boston, Appendix D, Page 462

Note: At this juncture, a polycarbonate certified with an Environmental Product Declaration (EPD) was selected to ensure the incorporation of materials with documented environmental assessments throughout their life-cycle, especially during A and C stages. The approach was designed to anchor the modeling framework in

robust environmental scrutiny, facilitating a comprehensive assessment of impacts during the operational phase (B6 stage) of the building's life cycle.

To quantify the annual environmental impact of polycarbonate, the researcher multiplied the outcomes derived from openLCA, as presented in the previous section, by the output data from Ladybug and Honeybee. Table 4.20 displays the environmental impact results, offering a comprehensive synthesis of the findings.

Table 4-58: The annual environmental impact (Polycarbonate) , Appendix D, Page 463

Thickness,Transmittance, U-value	Acidification	Carcinogenic	Ecotoxicity	Eutrophication	Fossil fuel depletion	Global warming	Non carcinogenic	Ozone depletion	Respiratory effects	Smog
0.025, 0.62, 1.4	141.7005	0.000611	69097.8502	46.124548	171347.6	80310.19	0.002704	0.010035	17.03551	1760.966
0.025, 0.11, 1.4	141.6724	0.000611	69084.1616	46.115411	171313.7	80294.28	0.002703	0.010033	17.03214	1760.617
0.025, 0.28, 1.4	141.7041	0.000612	69099.6283	46.125735	171352	80312.26	0.002704	0.010035	17.03595	1761.011
0.025, 0.08, 1.4	141.6807	0.000611	69088.1982	46.118105	171323.7	80298.97	0.002703	0.010034	17.03313	1760.72
0.025, 0.67, 1.6	142.511	0.000615	69493.088	46.388379	172327.7	80769.56	0.002719	0.010093	17.13295	1771.039
0.032, 0.64, 1.25	139.1491	0.0006	67853.7202	45.29406	168262.4	78864.18	0.002655	0.009855	16.72878	1729.259
0.032, 0.07, 1.25	139.2055	0.000601	67881.2102	45.31241	168330.6	78896.13	0.002656	0.009859	16.73556	1729.96
0.032, 0.33, 1.25	139.1609	0.000601	67859.4457	45.297882	168276.6	78870.83	0.002655	0.009855	16.73019	1729.405
0.032, 0.04, 1.25	139.5694	0.000602	68058.6429	45.430851	168770.6	79102.36	0.002663	0.009884	16.7793	1734.482
0.035, 0.63, 1.2	138.0048	0.000596	67295.6942	44.921564	166878.6	78215.6	0.002633	0.009774	16.5912	1715.038
0.035, 0.07, 1.2	138.4173	0.000597	67496.8484	45.055839	167377.5	78449.4	0.002641	0.009803	16.6408	1720.164
0.035, 0.33, 1.2	138.0287	0.000596	67307.3418	44.929339	166907.5	78229.14	0.002634	0.009775	16.59408	1715.335
0.035, 0.04, 1.2	138.4583	0.000597	67516.8263	45.069175	167427	78472.62	0.002642	0.009806	16.64572	1720.673

4.2.4.5 Discussion and primarily analysis

In this section, a comprehensive analysis of how variations in the physical properties of polycarbonate, specifically thickness, transmittance, and U-value, influence the energy consumption for cooling, heating, and lighting in buildings has been presented. Using data extracted from Excel spreadsheets, diagram 4.31 has demonstrated the individual and collective effects of these parameters on energy usage.

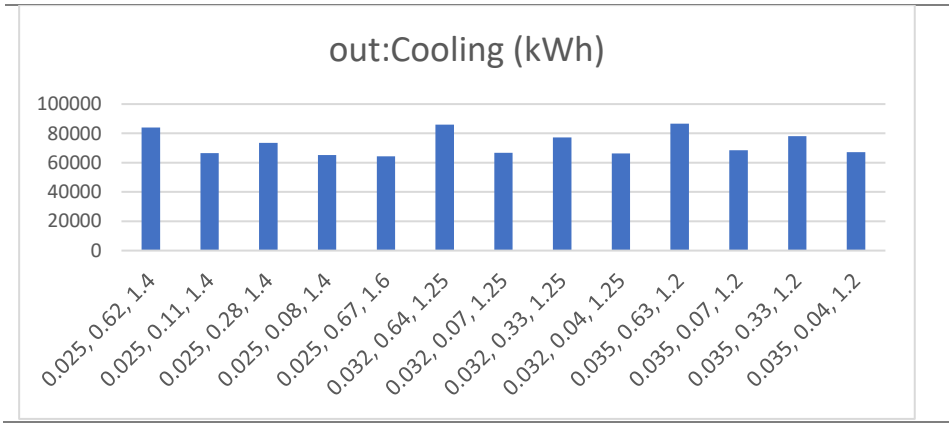




Diagram 4-31: Impact of Varied Polycarbonate Features on Building Energy Consumption, Appendix C, Page 433

Upon conducting a comparative analysis of the energy performance of various polycarbonate cladding systems, it was observed that the system with a thickness of 0.035 meters, a light transmittance of 0.63, and a U-value of 1.2 is less energy-efficient concerning cooling energy consumption compared to its counterpart. It exhibited a 25.69% higher energy usage, amounting to 86,561.66 kWh. Conversely, a system featuring a reduced thickness of 0.025 meters, an increased transmittance of 0.67, and a higher U-value of 1.6 resulted in increased heating energy consumption, utilizing 275,815.10 kWh, which is 13.68% more than the 242,631.44-kWh required by the system with greater thickness and a lower U-value. Both systems had identical lighting energy requirements of 6,150.06 kWh, suggesting that light transmittance does not significantly affect their lighting efficiency. Overall, in terms of total energy consumption, the system with a thickness of 0.035 meters proved to be more efficient, using approximately 3.27% less energy compared to the system with a thickness of 0.025 meters. This analysis highlights the significant influence of polycarbonate material properties on the energy dynamics of building envelopes, particularly the impact of thickness and U-value on thermal efficiency and the resulting heating and cooling energy demands, while transmittance seems to have a minimal effect on lighting energy consumption.

The bar charts presented below offer a visualization of the results to enhance the understanding of the effects that changes in the physical properties of polycarbonate have on various outcomes (diagram 4.32).

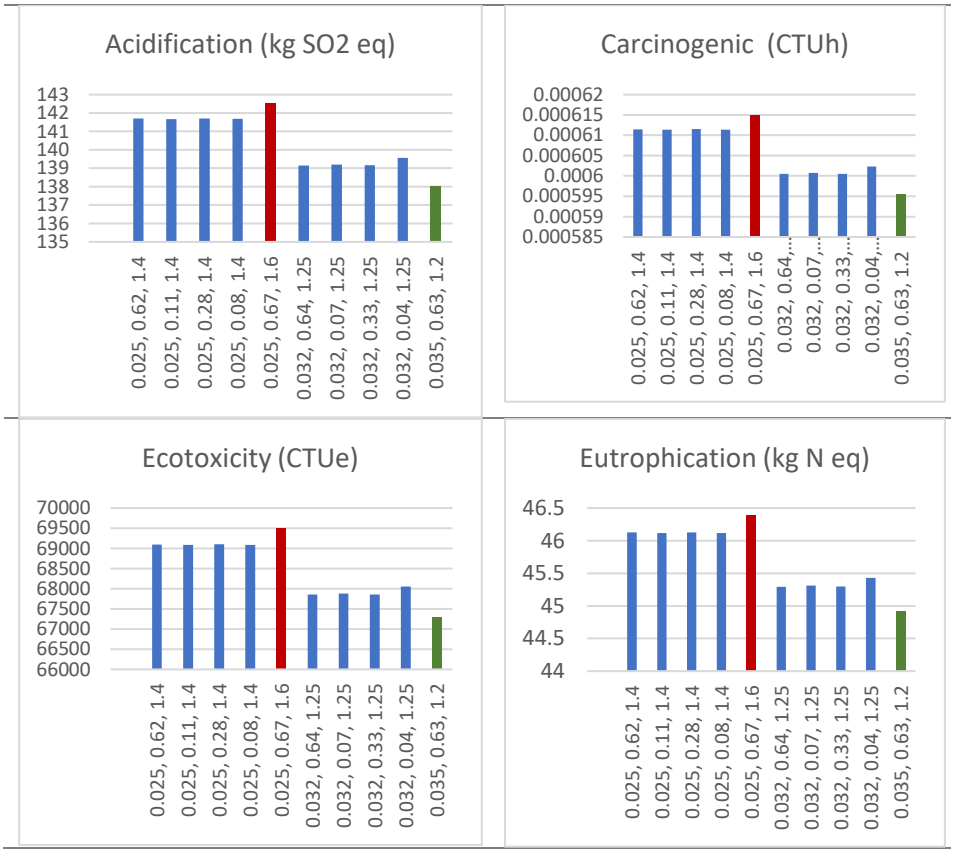




Diagram 4-95: Impact of Varied Polycarbonate Features on Building environmental impact on B1 stage, Appendix C, Page 434

Upon evaluating the environmental impact of different polycarbonate cladding systems, a meticulous assessment reveals that the system with a marginally thicker profile of 0.035, a lower transmittance of 0.63, and a lower U-value of 1.2 manifests slightly less environmental impact across a spectrum of categories when compared to the system with a 0.025 thickness, a higher transmittance of 0.67, and a higher U-value of 1.6. The comparative analysis indicates that the latter configuration results in an

increase of 3.27% in acidification (an additional 4.51 kg SO_2 eq), carcinogenic potential (an increase of 0.000019%), ecotoxicity (a rise of 2197.39 CTUe), and eutrophication (an increment of 1.47 kg N eq). Furthermore, it accounts for a 3.27% augmentation in fossil fuel depletion (by 5449.06 MJ surplus), global warming potential (an increase of 2553.96 kg CO_2 eq), non-carcinogenic effects (a 0.000086 CTUh increase), ozone depletion (a 0.000319 kg CFC-11 eq rise), respiratory effects (an additional 0.54 kg $PM_{2.5}$ eq), and smog formation (an increase of 56.00 kg O_3 eq). The most pronounced difference is observed in the category of smog formation, which underscores the notable dependency of environmental impact on the physical characteristics of the cladding materials. This comparative percentage difference elucidates the nuanced, yet discernible environmental implications associated with the selection of polycarbonate cladding materials based on their thickness, transmittance, and U-value.

4.2.5 Hybrid Cladding System

4.2.5.1 A review of the Modeling strategy in Phase 3

In the third phase of modeling, an innovative approach was undertaken, focusing on the development of a hybrid model integrating aluminum and polycarbonate materials for optimization. While previous investigations underscored the superior performance of the aluminum system over the polycarbonate counterpart, a crucial aspect overlooked was the incorporation of daylight utilization within the former. Recognizing daylight utilization as pivotal for fostering environmentally conscious building design, the exclusive emphasis on energy consumption efficiency during the operational phase rendered the aluminum system suboptimal.

Driven by the hypothesis that a composite system could yield enhanced performance, the fusion of aluminum and polycarbonate materials was explored. The optimization strategy in the third phase diverged from previous approaches, which primarily focused on varying material properties and thicknesses. In the preceding phases, variations were explored in material features and thickness for both aluminum and polycarbonate roofs. For aluminum, the optimal thickness determined in the previous phase was retained, based on its performance as a single cladding system. However, for polycarbonate, the parameters considered included thickness, U-value, and conductivity, reflecting a broader spectrum of variables. Given the predictable outcome associated with energy consumption reduction through thickness and U-value improvements, a multifaceted optimization approach was adopted. This approach sought to address not only energy consumption but also spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) to ensure comprehensive optimization. By incorporating these three goals, the optimization process could effectively capture the nuanced performance dynamics of the hybrid system.

The optimization process involved partitioning the model into four distinct geographic zones, enabling a meticulous examination of aperture configurations aligned with solar movement patterns. Furthermore, adherence to LEED certification standards necessitated determining optimal aperture percentages for each façade. Leveraging the wallacei optimization algorithm, the computational framework facilitated the exploration of a vast design space. The exhaustive search encompassed an extensive set of 1,104,150,528 models, from which a subset of 7,500 models was judiciously selected for benchmarking purposes.

In this selection process, 100 genes were identified utilizing the WALLACEI component (an evaluation and analytic engine for grasshopper 3D) with a parameter setting of 75 generations and 100 genes for each generation, ensuring comprehensive coverage of design variations. Subsequently, the identified models underwent rigorous evaluation against predefined performance metrics, culminating in the identification of optimal design configurations. This methodological rigor not only enriched the understanding of hybrid material performance but also underscored the efficacy of a multifaceted optimization approach in architectural design paradigms. Figure 4-18 shows the visualization of Hybrid system. Figure 4.18 shows a visualization of the Hybrid system.

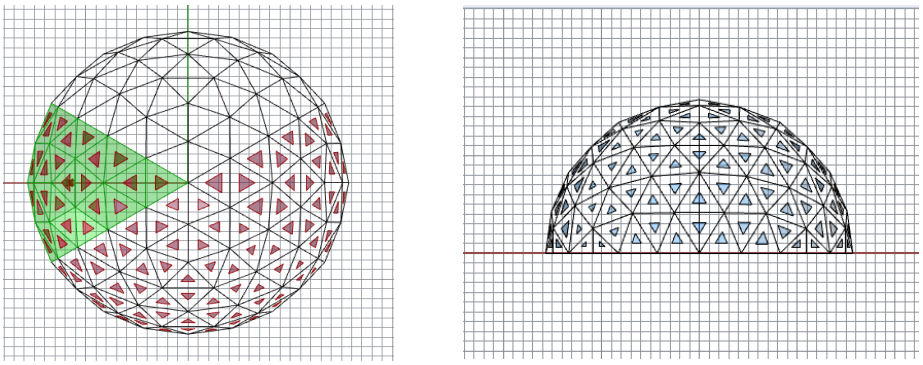


Figure 4-52: Visualization of Hybrid system

4.2.5.2 Introduction of WALLACEI

The name 'Wallacei' honors Alfred Russel Wallace, the renowned naturalist, explorer, and geographer who independently co-discovered the theory of evolution by natural selection alongside Charles Darwin. Wallacei (including Wallacei Analytics and Wallacei X) is a sophisticated evolutionary modeling platform designed for use within Grasshopper 3D. It empowers users to construct and execute evolutionary simulations, leveraging extensive analytical capabilities and diverse selection methodologies. This integrated environment facilitates informed decision-making throughout the evolutionary process, from problem definition and results analysis to the identification of optimal solutions. Moreover, Wallacei allows users to isolate, reconstruct, and export any phenotypic form from the simulated population. This streamlined free plugin optimizes data access, enabling efficient analysis and selection. Its aim is to enhance simulation comprehension, promote quantitative understanding, and streamline the extraction of optimized data within a single interface for users of all experience levels. While optimized for Rhino 6, Wallacei is compatible with Rhino 5 and Rhino 7 WIP (Makki, Showkatbakhsh, and Song 2019)

Wallacei X is the core element of the Wallacei platform. It provides a unified interface for users to execute evolutionary algorithms, perform in-depth analysis of results, apply diverse selection strategies, export phenotypes, connect to the online forum, and consult the included primer. All components previously offered in 'Wallacei Analytics' are seamlessly integrated into Wallacei X. The platform primarily uses the NSGA-2 algorithm (Chaube, Benyoucef, and Tiwari 2012) (Deb et al. 2002)for its evolutionary processes and leverages K-means clustering for analysis. Wallacei X also incorporates the open-source libraries JMetal, LiveCharts, and HelixToolkit for its functionality.

Figure 4.19 shows some settings and analytics in wallacei x component.

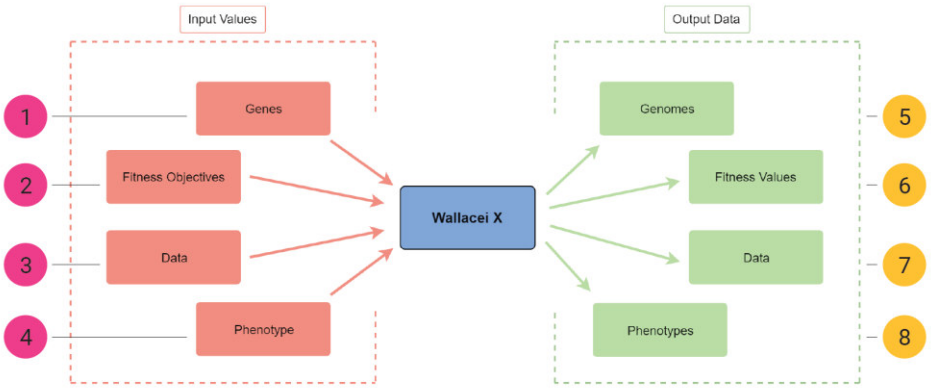


Figure 4-55: Input and out put data in Wallacei x,(Ref:(Makki et al. 2019)

① Genes are comprised of sliders or gene pools. Rename the sliders/gene pools with prefix 'wlc_' for automated selection (by right clicking the Wallacei X component and clicking 'Select all Sliders').
② Fitness Objectives are values contained within a 'number' component. Rename the fitness objectives with the prefix 'wlc_' for automated selection (by right-clicking the Wallacei X component and clicking 'Select all Objectives').
③ Any data type to be saved for every solution in the population (it is recommended only numerical data is inputted to avoid CPU overload causing grasshopper/rhino to crash).
④ The phenotypes that will be exported through the solver. Any data type is accepted such as Breps, Meshes, or Numbers (the phenotypes can be inputted after you run the simulation).
⑤ This outputs the genomes of all solutions in the population. To access the Genome, use the 'Decode Genome' component to extract numerical values comprising each solution's genome.
⑥ This outputs the fitness values of all solutions in the population. The list structure is as follows {A;B}[i], where 'A' is the generation number, 'B' is the solution number and 'i' is the fitness values for each fitness objective
⑦ This outputs the input data of all solutions in the population.
⑧ This outputs the phenotypes of the exported solutions. To access the geometry within the phenotype, use the 'Decode Phenotypes' or 'Distributor' components, which will output the data into different streams (numbers, meshes, breps, etc.)

This overview of Walleci sets the stage for its detailed applications described in both the preceding and following discussions. Specifically, paragraph 4.2.5.1 elaborates on the use of Walleci for identifying optimal design configurations through a robust evaluation process, illustrating the software's pivotal role in the methodology applied throughout this research.

4.2.5.3 Model Features

The model was partitioned into four distinct geographic regions to facilitate the optimization of aperture configurations relative to solar trajectory, aligning with criteria stipulated by the LEED certification standards. Table 4-21 presents the surface area measurements for each geographic direction, as well as the total surface area of the sphere.

Table 4-61: The Area of each geographic direction, Appendix D, Page 463

Geographic direction	**North (m^2)**	**East (m^2)**	**Sout (m^2)**	**West (m^2)**
Area	492.067396	267.728699	492.067396	267.728699
All surface Area	1519.59219 (m^2)			
Base area	758.855686			

In order to enhance control over light absorption, the spatial structure was deliberately designed using parametric cells. This architectural approach allowed for precise manipulation of the structural characteristics, facilitating the integration and customization of openings based on specific lighting requirements. The parametric design not only supported the efficient installation of these features but also enabled dynamic adjustments to the structure's interaction with light, thereby optimizing environmental performance and visual comfort within the space. Table 4-22 displays the maximum and minimum areas of each cell, categorized by their respective directions.

Table 4-64: Max and Min Area of each cell, Appendix D, page 463

	North	East	Sout	West
Min Area **(m^2)**	4.441	5.354	4.441	5.354
Max Area **(m^2)**	11.268	11.268	11.268	11.268

As such, the optimization objectives were delineated as follows:

- ✓ Minimization of energy consumption.
- ✓ Achievement of spatial Daylight Autonomy (sDA) exceeding 50 (sDA>50).
- ✓ Limitation of Annual Sunlight Exposure (ASE) to a value below 10.(ASE<10)

These objectives were selected to ensure that the resulting architectural design not only minimizes energy usage but also maximizes daylight utilization while adhering to established environmental performance benchmarks outlined in LEED certification criteria.

Given that each facade of the dome has been designated as a separate zone to precisely delineate the percentage of openings, a method has been devised to control the pattern of these openings, which can also be utilized as a shading pattern. The proposed method involves measuring the distance from the center of all generated cells on the dome to the assumed position of the sun. This measurement influences the design such that the closer a window is to the sun's position, the smaller its dimensions or opening percentage should be, and conversely, the further away it is, the larger it should be. Consequently, relative to the sun's position at the center of the dome, the dimensions of the cells are remapped and scaled according to minimum and maximum values. Figure 4-20 shows the visualization of this method.

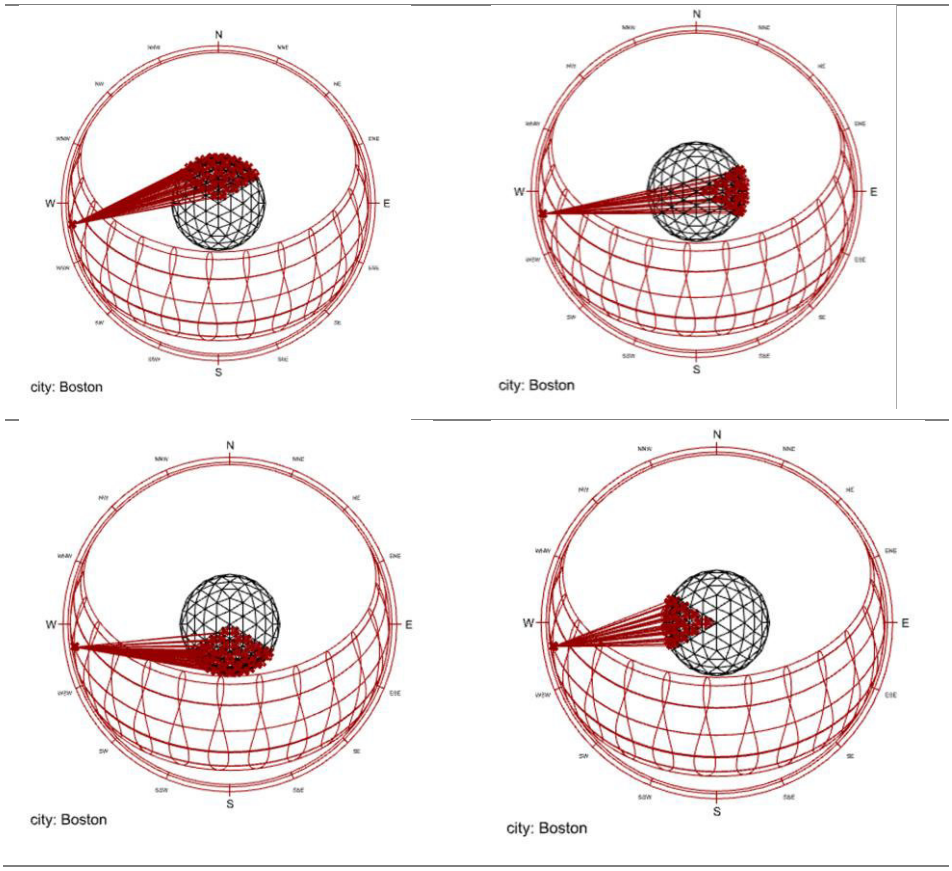


Figure 4-58: The central point distance of per cell to sun location, (Reference: Author, ABITAlab)

Consequently, utilizing this method enables the area of each cell to vary between minimum and maximum values depending on its geographic orientation. Table 4.23 displays the minimum and maximum areas of each cell across different geographic directions.

Table 4-67: Max and Min Area of each cell, Appendix D, Page 463

	North	East	Sout	West
Min Area **(m²)**	4.441	5.354	4.441	5.354
Max Area **(m²)**	11.268	11.268	11.268	11.268

Material Features: The determination of material features for the aluminum cladding system was informed by the optimized model from the preceding phase. These features were then delineated accordingly. Table 4.24 provides a comprehensive overview of the specified features of the aluminum cladding system, elucidating its structural attributes in detail.

Table 4-70: Aluminum Cladding system features, Appendix D, page 464

Material	**Thickness**	**Thermal conductivity**	**Density**
Kalzip profile sheet (Aluminum alloy EN AW-3004,3005, 3105, 6025)	1.2 mm	200 w/m.k	2700 kg/m³
XPS, polystyrene Insulation (/EN 12667/ and /EN 13164/ Annex C)	0.2 m	0.034 W/(mK)	20 - 50 kg/m3
Vapor control layer		-	-
Trapezoidal deck	1.2 mm	200 w/m.k	2700 kg/m³

The polycarbonate cladding system feature is shown in Table 4.25.

Thickness (mm)	Product	Light Transmission	U-Value (W/m2 K)	Nominal Sheet Weight (kg/m2)	Standard Sheet Sizes
25	Clear (PC25-C)	62%	1.4	3.1	Maximum Width: 2100mm Standard Max Length: 7m (and CTS)
	Bronze (PC25-B)	11%			
	Opal (PC25-O)	28%			
	Bronze/Opal (PC25-B/O)	8%			
	Solar guard (PC25-SG)	7%	1.6	3.4	
32	Clear (PC32-C)	64%	1.25	3.6	Maximum Width: 2100mm Standard Max Length: 7m (and CTS)
	Bronze (PC32-B)	7%			
	Opal (PC32-O)	33%			
	Bronze/Opal (PC32-B/O)	7%			
	Solar guard (PC32-SG)	4%	1.25	3.4	
35	Clear (PC35-C)	63%	1.2	3.9	Maximum Width: 2100mm Standard Max Length: 7m (and CTS)
	Bronze (PC35-B)	7%			
	Opal (PC35-O)	33%			
	Bronze/Opal (PC35-B/O)	7%			
	Solar guard (PC35-SG)	4%	1.2	3.4	

Table 4-73: Polycarbonate cladding system, Appendix D, Page 464

In instances where material specifications are not explicitly defined, the software defaults to utilizing data from the ASHRAE 90.1-2019 standard. This standard, being the most current version integrated into the Ladybug software, serves as a reliable reference for material properties (Figure 4.21).

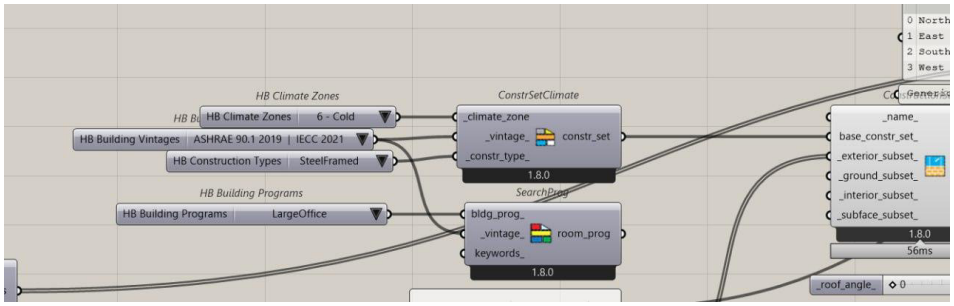


Figure 4-61: Defining the standards, (Reference: Author,ABITAlab

Model Function and lighting guidelines: For daylighting considerations, a grid model function was established, with grid dimensions set at 1.5 meters by 1.5 meters. The height of the grids is 75 centimeters, with a sensor positioned centrally within this height (Figure: 4.22).

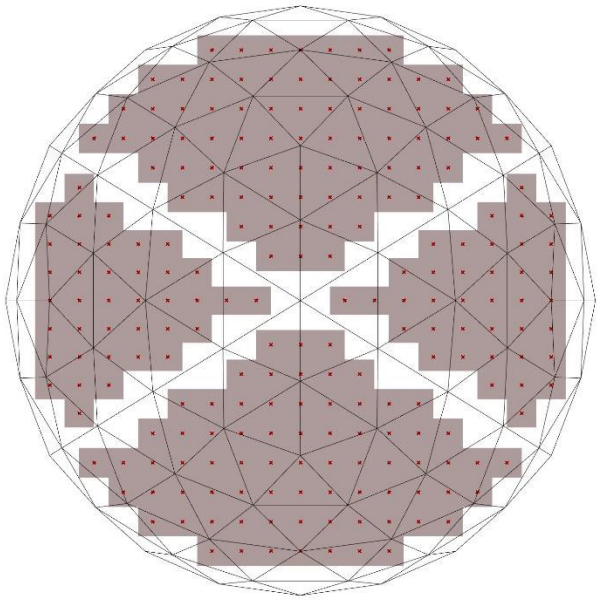


Figure 4-64: Grid model, (Reference: Author, ABITAlab)

Artificial lighting is coordinated with natural lighting, incorporating an intelligent lighting system. Each zone's illumination level must achieve 400 lux (based on ASHRAE standards) using natural light. Otherwise, the artificial lighting system adjusts illumination to meet standard thresholds (Figure 4.23).



Figure 4-67: defining lighting standards, (Reference: Author, ABITA lab)

To address the issue of variability in the percentage of polycarbonate openings throughout the area and to allow for adjustments relative to an environmental parameter, a specific date and time from the solar position during the equinox period on March 21st were selected. This temporal reference enables the adaptation of the range of polycarbonate openings from one interval to another due to the influence of this external factor. The fixed consideration of date, time, and month was motivated by the complexity inherent in simulation scenarios. Fixing the date, time, and month not only necessitated an increase in the number of models but also mandated the execution of distinct optimizations for each hour, day, and month, which diverged from the primary objective of this study.

The initial shape was divided into cells, and the distance from the center of each cell to the sun is variable to adjust the opening relative to the sun. These adjustments are made to optimize the area of each cell and to identify options that comply with the Annual Sunlight Exposure (ASE) and Spatial Daylight Autonomy (sDA) standards. This range was applied to meet LEED requirements (Figure 4.24).

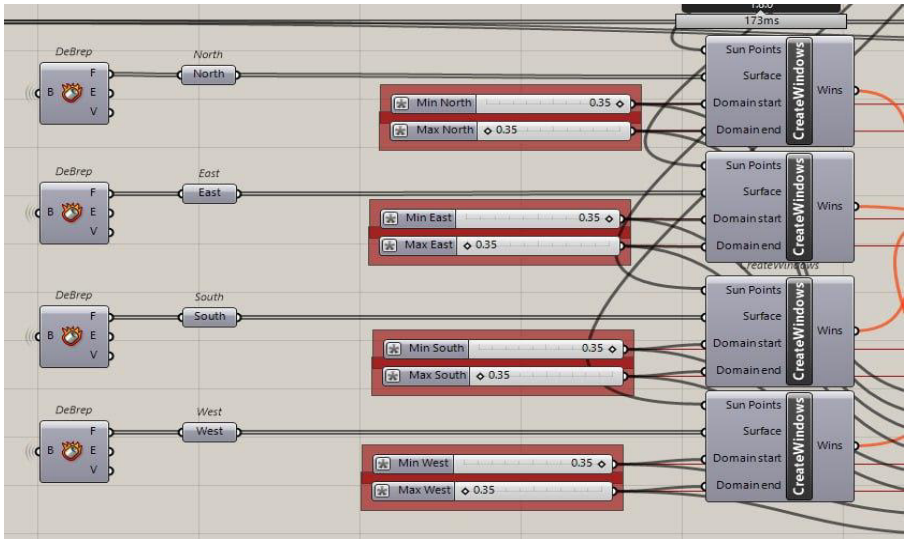


Figure 4-70: Percentage of Openings Across Geographic Facades, (Reference: Author, ABITAlab)

Cooling and Heating system features: The cooling and heating system features are outlined as follows: Set point cooling = 28°C, Set point heating = 20°C, System type = Ideal Air Load. The set point denotes the temperature threshold at which the system is programmed to deactivate (Figure 4.25).

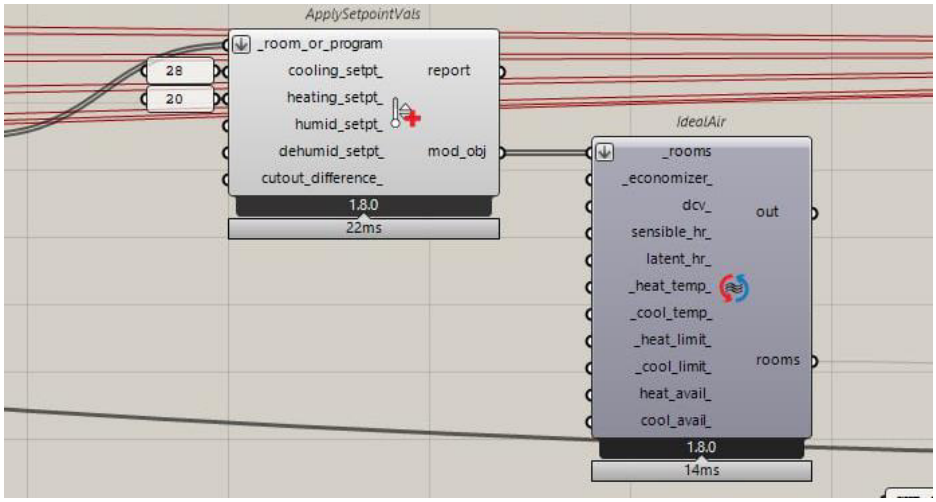


Figure 4-73: Defining the cooling and heating system features, (Reference: Author, ABITAlab)

4.2.5.4 Optimization

The optimization process employed Wallacei X (version 2.7), a Grasshopper component specializing in multi-objective evolutionary algorithms. To balance exploration and convergence, a generation size of 75 and a generation count of 100 were selected, resulting in a population size of 7,500 (Figure 4.26).

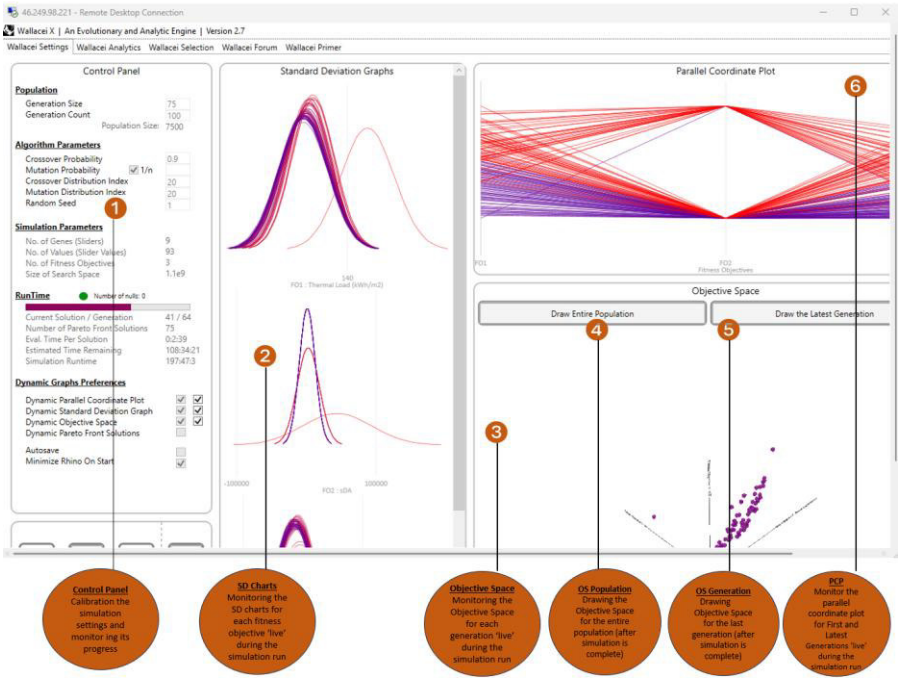


Figure 4-76: Wallacei settings, (Reference: Author, ABITAlab

This configuration enabled the NSGA-II algorithm to iteratively refine the 1,104,150,528 models generated from the initial parameter space. Wallacei's integrated analytics, including Unsupervised Machine Learning, Parallel Coordinate Analysis, and Pareto Front Analysis, were then leveraged to systematically explore the complex solution space and isolate the most optimal designs based on the specified objectives.

4.2.5.5 Results and Discussion

The output from Ladybug presents calculations for 7,500 models (Table 4.26).

	A	B	C	D	E	F	G	H	I	J	K	L
1	TP	MinN	MaxN	MinE	MaxE	MinS	MaxS	MinW	MaxW	TL (kwh/m2	sDA	ASE
2	3	0.05	0.6	0.25	0.7	0.15	0.55	0.35	0.4	145.4575	1E-05	23.9
3	8	0	0.5	0.1	0.9	0.25	0.7	0.1	0.7	158.8421	1E-05	26.62
4	8	0.25	0.85	0.05	0.5	0.15	0.8	0.05	0.8	176.3492	1E-05	12.5
5	4	0.3	0.85	0.2	0.8	0.25	0.35	0.35	0.8	194.7318	1E-05	22.87
6	10	0	0.65	0.2	0.5	0.35	0.75	0.15	0.6	154.5151	1E-05	26.96
7	8	0.25	0.6	0.1	0.6	0.2	0.45	0.1	0.75	137.075	1E-05	0.658
8	5	0.05	0.85	0.05	0.9	0.15	0.7	0	0.4	172.5938	73.65	54.75
9	3	0.05	0.5	0.2	0.5	0.35	0.85	0.3	0.45	163.2011	1.689	28.95
10	1	0.05	0.6	0.35	0.6	0.25	0.85	0.05	0.6	163.7505	7.095	35.19
11	4	0	0.6	0.15	0.6	0.15	0.35	0.2	0.8	125.9108	1E-05	3.948
12	10	0.25	0.4	0	0.9	0.1	0.85	0.15	0.5	157.3942	1E-05	38.68
13	1	0.05	0.55	0.15	0.6	0.2	0.5	0	0.45	119.5755	1E-05	18.03
14	3	0.15	0.75	0.05	0.5	0.3	0.9	0.1	0.9	188.3917	2.365	29.34
15	8	0.3	0.75	0.35	0.7	0.25	0.45	0	0.35	158.5455	1E-05	2.633
16	2	0.05	0.5	0.05	0.4	0.3	0.6	0.3	0.9	143.1936	24.29	28.61
17	1	0.3	0.75	0.3	0.4	0.1	0.45	0.25	0.45	147.9244	1E-05	10.74
18	1	0.25	0.7	0.1	0.4	0.2	0.5	0.1	0.7	140.9705	1E-05	14.19
19	7	0.05	0.65	0.25	0.5	0.1	0.65	0.05	0.9	140.3188	28.17	29.8
20	10	0	0.55	0.3	0.8	0.1	0.8	0.3	0.6	160.1002	1E-05	34.66
21	3	0.25	0.8	0.15	0.8	0.3	0.65	0.05	0.55	185.4915	1E-05	43.8
22	5	0.3	0.35	0.25	0.9	0.3	0.5	0.3	0.7	166.5679	94.62	50.98
23	5	0.15	0.65	0.1	0.6	0.3	0.55	0.1	0.75	145.6552	73.33	44.19
24	10	0.1	0.9	0.1	0.6	0.05	0.4	0.35	0.6	151.0769	1E-05	7.005
25	10	0.1	0.6	0.3	0.5	0.1	0.35	0.05	0.5	110.7966	1E-05	1.315
26	11	0.05	0.4	0.15	0.7	0.3	0.7	0.15	0.6	139.2096	45.39	43.74
27	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
7476	5	0.3	0.4	0.35	0.4	0.35	0.35	0.35	0.4	98.16269	45.71	3.325
7477	5	0.3	0.35	0.3	0.4	0.2	0.35	0.35	0.6	119.0443	79.3	8.98
7478	5	0.35	0.35	0.25	0.4	0.25	0.35	0.3	0.7	102.8612	67.07	14.05
7479	5	0.35	0.35	0.35	0.4	0.25	0.35	0.35	0.35	73.32732	24.66	8.785
7480	5	0.3	0.35	0.35	0.4	0.25	0.35	0.3	0.5	105.9406	67.64	9.123
7481	5	0.35	0.35	0.35	0.4	0.1	0.35	0.3	0.6	95.83827	51.42	7.253
7482	5	0.35	0.35	0.2	0.4	0.1	0.35	0.3	0.6	92.5549	45.82	5.28
7483	5	0.35	0.35	0.35	0.4	0.25	0.35	0.3	0.6	88.9295	48.67	9.443
7484	5	0.35	0.35	0.35	0.4	0.1	0.35	0.35	0.45	81.39056	26.74	2.648
7485	5	0.35	0.35	0.3	0.4	0.35	0.35	0.35	0.45	87.6371	46.05	7.235
7486	9	0.35	0.4	0.3	0.4	0.35	0.35	0.35	0.4	109.6708	63.16	5.638
7487	5	0.3	0.4	0.35	0.4	0.05	0.35	0.35	0.45	103.1132	49.36	3.663
7488	5	0.35	0.35	0.35	0.5	0.25	0.35	0.3	0.65	105.8484	73.01	19.31
7489	5	0.35	0.35	0.35	0.4	0.25	0.35	0.3	0.6	101.9822	72.69	15.36
7490	5	0.35	0.35	0.3	0.4	0.25	0.35	0.35	0.4	97.67419	68.39	16.02
7491	5	0.35	0.35	0.35	0.4	0.15	0.35	0.05	0.4	71.72892	7.095	1.353
7492	5	0.35	0.35	0.35	0.4	0.35	0.35	0.3	0.45	74.54052	19.74	0
7493	5	0.35	0.35	0.25	0.4	0.35	0.35	0.3	0.7	91.36198	44.74	5.263
7494	9	0.3	0.35	0.35	0.4	0.35	0.35	0.35	0.4	94.75561	38.99	1.653
7495	5	0.3	0.35	0.3	0.5	0.2	0.35	0.3	0.5	118.1764	83.59	12.27
7496	5	0.3	0.4	0.3	0.4	0.25	0.35	0.3	0.6	121.5152	87.12	13.43
7497	5	0.35	0.35	0.35	0.4	0.2	0.35	0.3	0.6	100.087	64.58	9.955
7498	5	0.35	0.35	0.35	0.4	0.35	0.35	0.35	0.45	88.81967	46.71	7.893
7499	5	0.3	0.35	0.35	0.4	0.25	0.35	0.3	0.6	121.6984	91.95	15.7
7500	5	0.35	0.35	0.35	0.4	0.1	0.35	0.35	0.45	81.39314	27.74	2.648
7501	5	0.3	0.4	0.3	0.4	0.2	0.35	0.35	0.4	118.6957	85.97	11.97
7502	5	0.35	0.35	0.3	0.4	0.2	0.35	0.25	0.65	96.03375	57.68	6.01

Table 4-76: initial data outputs, Appendix D, Page 465

Figure 4.27 presents the analytical diagrams for Wallacei, illustrating that the optimization process has been successfully executed. it includes standard deviation chart, fitness value chart, standard deviation Trendline for all generation, and mead value Trendline for all generation. These diagrams are crucial for verifying the accuracy and efficacy of the optimization, providing a clear visualization of the outcomes and parameters involved.

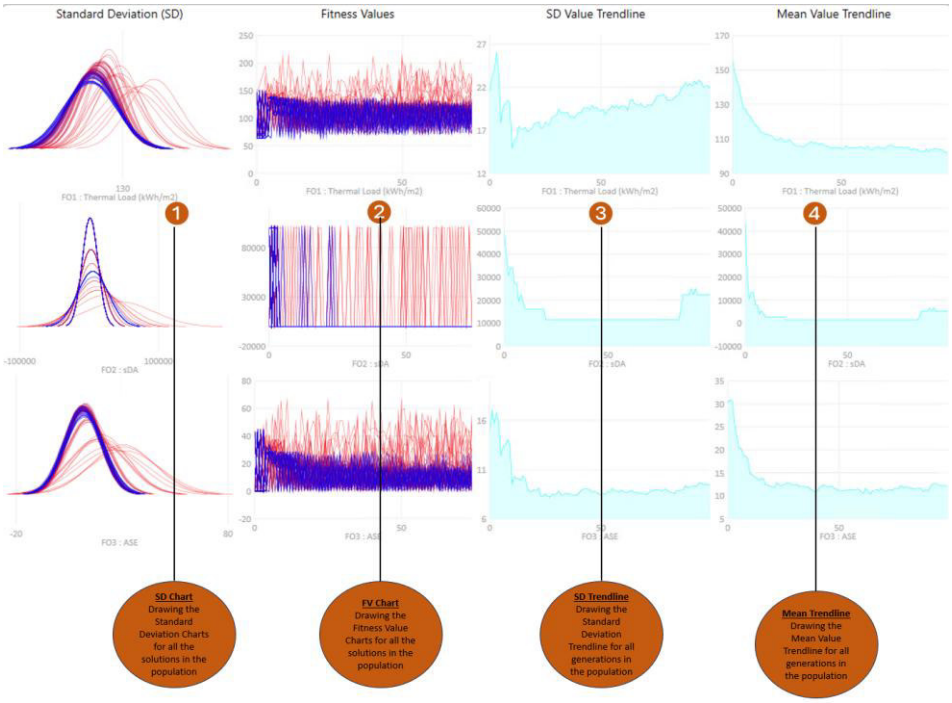


Figure 4-79: wallacei analytic

A summary and explanation of each diagram and its function have been provided below:

① Standard Deviation Chart (red to blue - first generation to last generation): Draws the standard deviation chart for all generations in the population for each fitness objective independently.

② Fitness Value Chart (red to blue - first generation to last generation): Draws the fitness value chart for all solutions in the population for each fitness objective independently.

③ Standard Deviation Trendline Chart: plotting the standard deviation values for each generation as a line chart (first to last generation are plotted from left to right) for each fitness objective independently.

Mean Value Trendline Chart:

④ Plotting the mean fitness value for each generation as a line chart (first to last generation are plotted from left to right) for each fitness objective independently.

Figure 4.28 illustrates the selection data from Wallacei among all outputs.

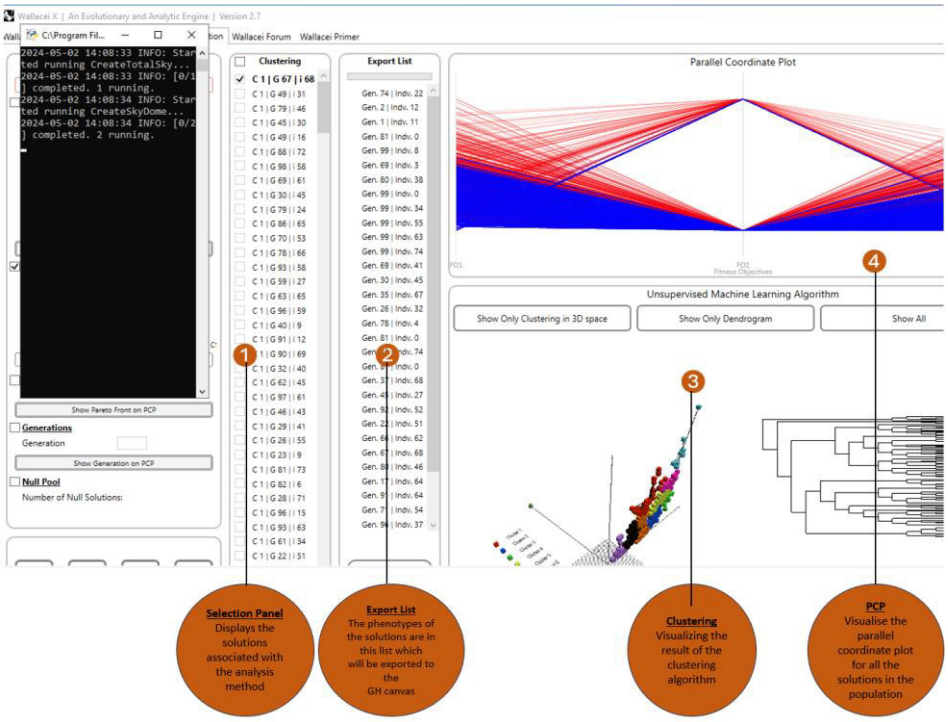


Figure 4-82: Wallacei selection(Reference: Author, ABITAlab)

① Selection Panel: Solutions corresponding to the analytic method chosen are displayed here.

② Export List: These are the solutions that will be exported to the canvas. When a user clicks the 'Export' button, a popup will appear with an estimated export time. It is important to note that this is an estimation only.

③ Clustering Viewport: Display the results of the Clustering algorithm. Kmeans clustering will display the results in the objective space only, however when running the Hierarchical clustering, the results can be displayed in the objective space as well as the dendrogram (which is the typical representation method for hierarchical clustering)

④ Parallel Coordinate Plot: displays the Parallel coordinate plot for ALL solutions in the population (red to blue - first solution to the last solution).

Among these data sets, Wallacei identified 30 models as the most optimized. Table 4.27 lists these models, showcasing the highest level of optimization achieved by Wallacei. The output data encompasses both maximum and minimum apertures in four distinct geographical directions: north, west, east, and south. Additionally, the data include thermal load, expressed in kilowatts per square meter per year (kW/m²/year), spatial daylight autonomy (sDA), and annual sunlight exposure (ASE). These metrics are essential for assessing the energy efficiency and lighting quality of architectural designs, allowing for optimized environmental performance across different orientations and climatic conditions.

TP	MinN	MaxN	MinE	MaxE	MinS	MaxS	MinW	MaxW	TL (kwh/m2)	sDA	ASE
5	0.25	0.45	0.3	0.4	0.2	0.35	0.3	0.7	125.1971	88.245676	10.63
5	0.3	0.35	0.1	0.5	0.25	0.35	0.35	0.45	118.935536	90.309762	20.963
5	0.3	0.35	0.2	0.4	0.2	0.35	0.3	0.45	112.627717	74.024724	7.6625
9	0.35	0.35	0.3	0.4	0.2	0.4	0.35	0.4	97.387288	66.392245	14.705
5	0.25	0.4	0.35	0.35	0.2	0.35	0.3	0.55	105.67458	60.507049	3.715
5	0.3	0.4	0.3	0.4	0.25	0.35	0.3	0.5	120.817915	93.049223	15.4
5	0.3	0.35	0.3	0.35	0.25	0.35	0.3	0.6	118.48388	86.400553	12.413
5	0.35	0.35	0.2	0.35	0.25	0.35	0.3	0.45	92.715945	50.978793	10.1
5	0.35	0.35	0.35	0.4	0.2	0.35	0.25	0.65	99.36136	65.612493	9.2975
5	0.35	0.35	0.35	0.4	0.25	0.35	0.35	0.5	101.501202	73.024682	16.678
5	0.35	0.35	0.35	0.35	0.05	0.35	0.05	0.4	69.51709	1.013514	0.3375
5	0.35	0.35	0.35	0.35	0.2	0.35	0.3	0.7	90.232067	43.936731	4.6925
5	0.35	0.4	0.35	0.4	0.25	0.35	0.35	0.45	125.957061	96.711799	18.368
5	0.35	0.35	0.3	0.4	0.2	0.35	0.3	0.4	93.672669	51.421813	8.64
5	0.35	0.4	0.3	0.45	0.3	0.35	0.35	0.65	135.092894	99.344327	29.073
5	0.35	0.35	0.35	0.35	0.1	0.35	0.35	0.4	80.205076	25.106703	2.6475
5	0.3	0.4	0.35	0.35	0.2	0.35	0.3	0.6	109.868765	68.259386	5.3875
5	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	64.039581	0.00001	0
5	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.4	75.475133	21.710341	1.9725
5	0.3	0.35	0.25	0.4	0.25	0.35	0.3	0.5	116.693595	84.047739	13.07
5	0.35	0.35	0.35	0.35	0.05	0.35	0.35	0.45	80.412565	26.049129	2.31
5	0.35	0.35	0.3	0.35	0.2	0.35	0.25	0.65	96.033746	57.680106	6.01
5	0.35	0.35	0.3	0.35	0.35	0.35	0.35	0.45	85.673049	40.789688	4.605
5	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	64.039581	0.00001	0
5	0.35	0.35	0.35	0.35	0.1	0.35	0.35	0.35	68.144747	4.054049	0.675
5	0.35	0.4	0.3	0.45	0.25	0.35	0.3	0.75	133.688594	99.000099	20.343
5	0.35	0.35	0.35	0.35	0.25	0.35	0.3	0.6	88.929498	48.666537	9.4425
5	0.35	0.35	0.35	0.35	0.15	0.35	0.05	0.4	71.728923	7.094614	1.3525
5	0.35	0.35	0.3	0.35	0.2	0.35	0.25	0.65	96.033746	57.680106	6.01

Table 4-27: optimized model based on wallacei analysis, Appendix D, Page 466

In the subsequent stage, data from the Ladybug analysis are imported into Design Explorer, a web-based platform designed to visualize and explore complex datasets. This tool is particularly useful in architectural and design contexts, as it facilitates the analysis of multiple variables and assists in identifying potentially optimal solutions based on specific criteria. Although Design Explorer does not perform linear optimization, it allows for the efficient navigation of extensive data, enabling the selection of effective design strategies through visual comparisons and interactive filtering. Initially, the objective was to optimize thermal loads, minimize Annual Sunlight Exposure (ASE), and maximize Spatial Daylight Autonomy (sDA). Specific constraints were set for these parameters: thermal loads were limited to under 100 kW/m²/year, sDA was targeted to exceed 50%, and ASE was constrained to less than 10%. Design Explorer facilitated iterative adjustments, displaying varying outcomes

with each modification. Ultimately, by narrowing the selection criteria, the results were generated, as presented in Diagram 4-33.

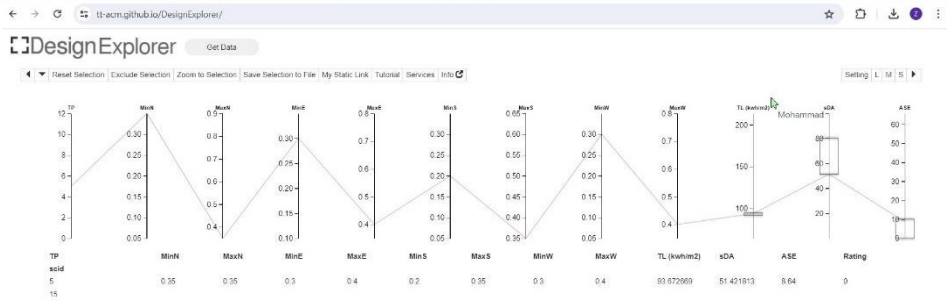


Diagram 4-98: Optimization wallacei data by design explorer, Appendix C, Page 436

In the second phase, the model results selected by Wallacei were imported into Design Explorer, with constraints applied based on the output limitations required to achieve LEED certification. Diagram 4.34 presents these results, illustrating how the adjusted parameters align with the stipulated LEED criteria.



Diagram 4-99: optimization all data output from ladybug, Appendix C, Page 436

Table 4-28 displays the results from the two-stage optimization process, which includes the optimized items from Wallacei data and the optimized model from all Ladybug data. The results from Wallacei indicate that Model type 5 is optimized, whereas the results from the comprehensive Ladybug data suggest that Model Type 9 is optimized.

Data group	Model Type	Thermal Load	sDA	ASE
Wallacei data	5	93.672669	51.421813	8.64
All data	9	93.236228	53.378883	7.325

Table 4-28: Two optimized model, Appendix D, Page 466

Table 4.29 provides a comparative analysis of two architectural glazing options, Model 5 and Model 9, as derived from simulation outputs using tools such as Ladybug for environmental analysis and Wallacei for optimization. Both models exhibit similar light transmission capabilities, with Model 5 allowing 64% and Model 9 permitting 63% of light to pass through, indicating their potential efficacy in applications requiring substantial natural light penetration. However, the thermal performance, as indicated by the U-value, shows a slight variance between the two; Model 5 has a U-value of 1.25 W/m²K, and Model 9 performs slightly better at 1.2 W/m²K, suggesting a lower rate of heat loss for Model 9 and thus a marginally improved thermal efficiency. Furthermore, the difference in thickness, with Model 5 at 32 mm and Model 9 at 35 mm, may imply a material composition adjustment or a design change aimed at enhancing thermal insulation without significantly compromising light transmission. These results are critical in assessing the trade-offs between natural lighting and energy efficiency in sustainable architectural design.

Table 4.29: the optimized model features, Appendix D, Page 466

Model type	Light Transmission	U-value (w/m2k)	Thickness (mm)
5	64%	1.25	32
9	63%	1.2	35

Table 4.30 provides insights into the optimized configuration of window openings in different geographic orientations for two model types, Model 5 and Model 9, using percentage values to indicate the proportion of openings. The data specifically addresses how each model utilizes openings to conform to sustainability standards and optimize energy efficiency.

Table 4-85: Optimized model result, Appendix D, page 467

Model type	Min N	Max N	Min E	Max E	Min S	Max S	Min W	Max W	TL (kwh/m2)	sDA	ASE
5	0.35	0.35	0.3	0.4	0.2	0.35	0.3	0.4	93.672669	51.421813	8.64
9	0.35	0.35	0.3	0.35	0.2	0.35	0.3	0.4	93.236228	53.378883	7.325

In both models, the North direction shows identical minimum and maximum values (0.35), indicating that there should be no openings (0% windows) on the northern facade. This approach likely aims to reduce heat loss and prevent low-angle sunlight glare, which is minimal from the north, thus optimizing thermal performance without compromising the interior light quality.

For the East and West directions, the percentages of light openings in each cell can be adjusted between minimum and maximum values, allowing for adaptable window sizes. Based on the distance from the center of each cell to the sun, Model 5 features openings ranging from 30% to 40% of each cell area for lighting in both the East and West directions. This flexibility facilitates enhanced morning and evening light exposure while mitigating significant heat gain. Conversely, Model 9 specifies a narrower range of 30% to 35% for the East direction, aimed at further reducing morning heat gain while still providing sufficient daylight.

In the South direction, which is optimal for solar heating, both models exhibit a variable range from 20% to 35%. This strategic variability in window openings maximizes solar gain during the winter and prevents excessive heat accumulation during the summer, thus maintaining a balance in energy requirements throughout the year. The Thermal Load (TL) values, which measure the total energy performance related to cooling and heating systems, are closely matched between the two models, suggesting that both

designs achieve a similar level of energy efficiency. Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) further detail the daylight and sun exposure aspects. Model 5 shows an sDA of 51.42% and an ASE of 8.64, indicating efficient daylight use with controlled sun exposure. Model 9 improves upon these metrics with an sDA of 53.38% and a lower ASE of 7.325, highlighting superior daylight integration and reduced glare.

4.2.5.5.1 Comparison of the Environmental Impact of Optimized Models

As a central aim of this thesis, identifying the optimal architectural model with the least environmental impact is paramount, especially within the context of promoting positive buildings. Table 4.31 presents the environmental impact analysis.

MT[1]	TL	AC	CA	ECO	EUT	FFD	GW	NCA	OD	RE	S
5	93.67267	0.03854938 9	1.6635E-07	18.79796	0.01254811	46.6148405 3	21.84826	7.355E-07	2.73007E-06	0.004634	0.479068
9	93.23623	0.03836977 9	1.6558E-07	18.71038	0.01248965	46.39765202	21.74646	7.321E-07	2.71735E-06	0.004613	0.476836

Table 4-88: Environmental Impact Analysis, Appendix D, page 467

This analysis integrates the thermal load, represented as electricity usage for heating and cooling systems, quantified in kWh/m² for each model. Model 5 records a thermal load of 93.672669 kWh/m², and Model 9 is slightly less at 93.236228 kWh/m², indicating that Model 9 is marginally more efficient in thermal energy management. This efficiency plays a crucial role when multiplied by the environmental impacts associated with the market for electricity at low voltage per kWh, which accounts for the entire lifecycle of electricity production and transmission.

In evaluating broader environmental metrics, there are nuanced differences between the models that influence their overall sustainability profiles. Model 5 exhibits slightly higher impacts in Acidification (0.038549389), Eutrophication (0.012548109), and Global Warming (21.84825972) compared to Model 9, suggesting it imposes a greater environmental load per unit of energy consumed. In contrast, Model 9 demonstrates lower impacts across these categories, as well as in Fossil Fuel Depletion (46.39765202) and Ozone Depletion (2.71735E-06), indicating a reduction in environmental burdens. Although these differences are modest, they may become significant when applied on a larger scale or over the building's operational lifetime. Therefore, the data suggest that Model 9, with its slightly lower thermal load and reduced environmental impact metrics, aligns better with the thesis's objectives to foster positive buildings through sustainable architectural design.

[1] Tl (Thermal Load , kwh/m2), AC (Acidification, kg SO_2 eq), CA (Carcinogenic, CTUh), ECO (Ecotoxicity, CTUe), EUT (Eutrophication, kg N eq), FFD (Fossil fuel depletion, MJ surplus), GW (Global warming, kg CO_2 eq), NCA (Non carcinogenic, CTUh), OD (Ozone depletion, kg CFC-11 eq), RE (Respiratory effect, kg PM2.5 eq), S (Smog, kg O_3 eq)

CHAPTER 5

Results, Interpretation, Conclusion, and Innovation

5.1 Abstract

The following chapter of this thesis, titled "Interpretation, Conclusion, and Innovation," synthesizes the findings of the research, addressing the initial research questions and investigating the hypotheses formulated at the outset. Through a comprehensive analysis, this chapter elucidates how the research objectives were achieved and the manner in which these accomplishments contribute to answering the overarching questions of the study. The focal point of the thesis—architectural principles for regenerative design of spatial structures to address positive buildings—serves as the foundation for a detailed discussion on the subject matter.

The research methodology employed in this study, coupled with the analytical and experimental data gathered, provided a robust framework for interpreting the findings. By systematically evaluating the effectiveness of various regenerative design principles in the architectural development of spatial structures, the study sheds light on their potential to engender positive impacts on buildings. This involves an assessment of sustainability, energy efficiency, environmental impact, and user well-being.

Challenges encountered during the research process are candidly discussed, highlighting the limitations and potential areas for further investigation. These challenges include, but are not limited to, the integration of regenerative design principles in conventional architectural practices, the scalability of such approaches, and the quantification of their impact.

Innovation emerges as a key theme in this chapter, where suggestions for future research and practice are proposed. Innovations in material technology, design methodologies, and architectural practices are identified as pivotal areas where advancements could significantly enhance the regenerative capacity of spatial structures. The chapter concludes with a call to action for architects, designers, and stakeholders in the construction industry to embrace and implement regenerative design principles, thereby contributing to the creation of positive buildings that are sustainable, energy-efficient, and harmonious with their natural surroundings.

This concluding chapter not only encapsulates the research findings but also paves the way for future inquiries into the field of regenerative architecture, underscoring the critical role of innovation in advancing the discourse on sustainable and positive building design.

5.2 Introduction of the chapter

In the quest to harness architectural innovations for sustainability, this thesis has embarked on a comprehensive journey to unravel the environmental implications of geometric forms and cladding materials in building design. Situated within the framework of regenerative design principles, this research has meticulously examined how strategic architectural choices can significantly reduce the environmental footprint of large office buildings, specifically in the context of Boston's climate. Through a dual-focused approach, the investigation has not only scrutinized various geometric configurations but also compared the efficacy of different cladding materials in pursuit of sustainable architectural solutions.

5.2.1 Research Recapitulation

The objectives of this thesis were set against a backdrop of regenerative design principles, aiming not only to minimize negative environmental impacts but also to enhance positive interactions between built structures and their surroundings. The research was meticulously structured around two primary goals: evaluating the impact of building geometry on environmental performance and investigating the sustainability potential of various cladding materials in operational phases.

5.2.2 Addressing the Research Questions and Hypotheses

The research was propelled by a set of well-structured research objectives and questions that sought to dissect the role of passive architectural strategies in enhancing building performance. The investigative journey began with the hypothesis that curved geometric forms would manifest a significant reduction in environmental impacts, specifically through lowered operational energy needs as evidenced by a reduced carbon footprint. Concurrently, the hypothesis concerning cladding materials projected that a strategic combination of aluminum and polycarbonate could transcend the environmental performance of single-material systems, not only in operational energy metrics but also in broader sustainability markers including sDA and ASE. The findings have compellingly validated these hypotheses, presenting the hybrid cladding system as a superior alternative capable of meeting and exceeding LEED standards, thereby endorsing its application in the design of positive buildings.

Therefore, both hypotheses were affirmed through rigorous simulations and analyses, providing compelling evidence that supports a paradigm shift in architectural practices towards more sustainable designs.

5.2.3 Chapter Structure

This chapter unfolds by first interpreting the complex data gathered and analyzed across various simulations, offering a deep dive into what these findings signify for the architectural community and sustainability discourse. Following this, a succinct conclusion will be drawn, encapsulating the overarching insights of the study. The chapter will culminate with strategic suggestions aimed at propelling forward the application of these research outcomes in real-world scenarios, thereby paving the way for future studies and practical implementations.

This chapter aims to synthesize these findings, offering a detailed interpretation that aligns theoretical frameworks with practical outcomes. It endeavors to draw robust conclusions from the data collected and analyzed, setting the stage for well-founded recommendations that could guide future architectural practices. Moreover, it seeks to outline potential avenues for further research that could continue to push the boundaries of knowledge in the field of sustainable architecture. The structure of this final chapter will follow a logical progression, beginning with a succinct summary of key findings before delving into a deeper interpretation of the results. Conclusions will be thoughtfully drawn to encapsulate the research insights, followed by pragmatic suggestions aimed at fostering the integration of the study's conclusions into real-world applications.

5.2.4 Forward-looking Statements

As we proceed, the insights garnered from assessing the sphere geometry's superior function in energy management, alongside the nuanced performances of aluminum and polycarbonate cladding systems, will be critically evaluated. The final recommendations will consider the operational exigencies of modern architectural designs, focusing particularly on the integration of these findings into current and future design frameworks that meet and exceed LEED certification standards.
By interlacing the empirical evidence with theoretical discourse, this chapter not only aims to validate the initial hypotheses but also to illuminate pathways for the incorporation of these findings into the broader context of sustainable architectural innovation.

5.3 Key findings of Section 1

5.3.1 Hypothesis and goals in Section 1

The initial hypothesis of this thesis proposed that spherical forms demonstrate enhanced environmental performance relative to cubic and cask geometries, particularly in the context of large office buildings in Boston's climate. This hypothesis underpins the development of design strategies that promote regenerative principles, contributing positively to the environmental impact of building structures. The research delineated two main objectives to explore this assertion comprehensively. The first objective involved a detailed analysis of how different geometric forms influence the environmental efficiency of office buildings, considering these forms as passive architectural solutions. This analysis was pivotal in pinpointing specific shapes that either boost or impair environmental performance based on climatic nuances. The second objective was to formulate design guidelines that optimize these geometric forms, aiming to enhance environmental sustainability. These guidelines are designed to transition from theoretical frameworks to practical tools that architects and designers can employ effectively in real-world scenarios. The findings elucidated in this section underscore the critical impact of form and shape on the sustainability of buildings, directly addressing the central research question and illustrating the practical application of theoretical architectural concepts. The summary of the first hypothesis and the associated goal is visually presented in Figure 5.1, providing a clear graphical representation of the analyzed data and conceptual frameworks.

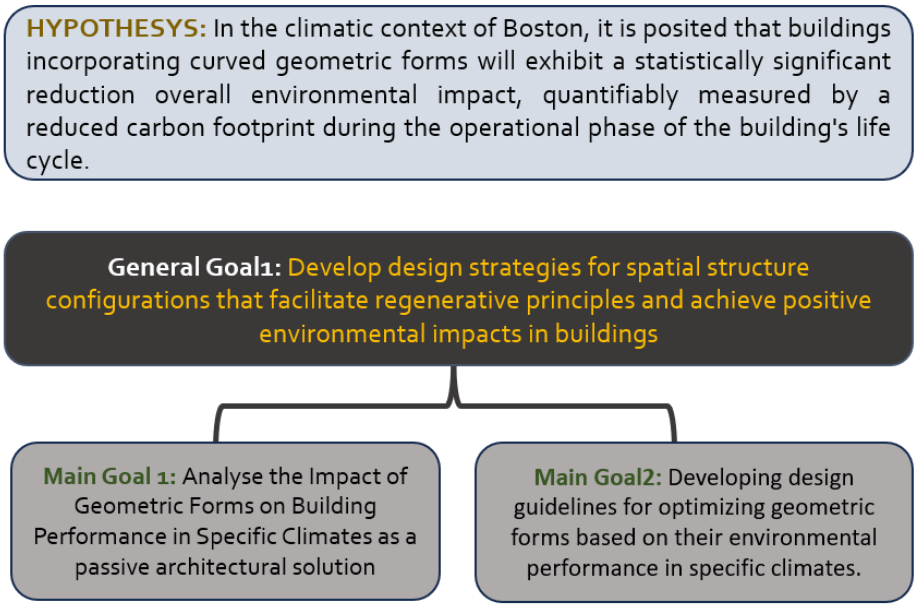


Figure 5-1: Hypothesis and goals in section 1

5.3.2 Exploring Geometric Forms: Research Questions and Methodological Approaches in Section 1

This section of the thesis seeks to answer the first general question regarding the environmental impact of architectural geometries. It investigates how the selection of specific shapes—cube, sphere, and cask—affects on environmental impact of large office buildings in Boston through the energy usage, particularly through their heating and cooling needs. To achieve this, the study employs advanced parametric modeling with Grasshopper, which is integrated into Rhino's suite of 3D modeling tools, allowing for precise and variable manipulations of form.

Utilizing environmental simulation plugins Honeybee and Ladybug, the study incorporates real-world climatic data into the model, enhancing the accuracy of the environmental impact assessment. This approach ensures that the study's findings are deeply contextualized within the climatic specifics of Boston, providing insights that are both relevant and applicable.

The methodological rigor is further evidenced by the extensive range of simulations—over 2000 for each form—designed to capture a broad spectrum of potential outcomes. To assess the life-cycle environmental impacts more accurately, the OpenLCA framework is employed, focusing specifically on the implications of electricity consumption in the operational phase of a building's life cycle. The dimensions and volumes of the modeled structures vary significantly, allowing the research to explore the impact of scale on environmental efficiency. The office prototype's spatial parameters are ranged, with floor areas between 100 square meters and 2500 square meters, and volumes from 380 cubic meters to 47,000 cubic meters.

Python is utilized for sensitivity analysis, specifically to analyze the effects of changing dimensions within each geometric form. It processes large datasets to identify how variations in dimensions influence the environmental impact caused by energy use

during the operational phase for each geometry. Additionally, Python assists in deriving parametric formulas to calculate outputs such as thermal load and environmental impacts. This sophisticated analytical approach not only enhances our understanding of how geometric dimensions affect building performance, but also reduces the need for complex modeling in the initial design stages.

5.3.2.1 Comparison the different Geometries

Three different models are presented by figure 5-2.

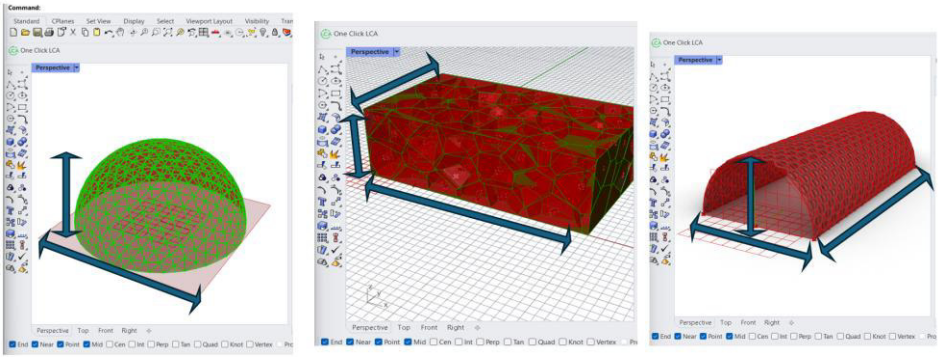


Figure 5-4: different geometries, Reference: Author , ABITAlab

Table 5.1 presents output data for each individual geometry, maintaining a constant area of 100 square meters.

Model	TL	AC	CA	ECO	EUT	FFD	GW	NCA	OD	RE	S
Sphere	6234.63856	2.565759	1.10721E-05	1251.149	0.835173453	3102.577	1454.17	4.9E-05	0.000182	0.308461	31.88566565
Cube	9010.65068	3.70818	1.60E-05	1808.231	1.207039698	4484.019	2101.649	7.08E-05	0.000263	0.445805	46.08295929
Cask	8264.14839	3.400969	1.47E-05	1658.425	1.107040493	4112.533	1927.534	6.49E-05	0.000241	0.408872	42.26514014

Table 5-2: Output data for each Geometry with 100-meter square area, Appendix D, Page 468

The result shows:

- **Thermal Load (TL):** The sphere has 30.81% less impact than the cube and 24.56% less impact than the cask.
- **Acidification (AC):** The sphere has 30.81% less impact than the cube and 24.56% less impact than the cask.
- **Carcinogens (CA):** The sphere has 30.80% less impact than the cube and 24.68% less impact than the cask.
- **Ecosystem Quality (ECO):** The sphere has 30.81% less impact than the cube and 24.56% less impact than the cask.
- **Eutrophication (EUT):** The sphere has 30.81% less impact than the cube and 24.56% less impact than the cask.

- **Fossil Fuel Depletion (FFD):** The sphere has 30.81% less impact than the cube and 24.56% less impact than the cask.
- **Global Warming (GW):** The sphere has 30.81% less impact than the cube and 24.56% less impact than the cask.
- **Non-Carcinogens (NCA):** The sphere has 30.79% less impact than the cube and 24.50% less impact than the cask.
- **Ozone Depletion (OD):** The sphere has 30.80% less impact than the cube and 24.48% less impact than the cask.
- **Resource Exploitation (RE):** The sphere has 30.81% less impact than the cube and 24.56% less impact than the cask.
- **Smog (S):** The sphere has 30.81% less impact than the cube and 24.56% less impact than the cask.

The pie charts provided illustrate a direct relationship between thermal load and overall environmental impacts across three geometric forms: Sphere, Cube, and Cask. The distribution patterns in both charts reveal how the thermal efficiency of a geometry directly correlates with its environmental impact.

In both "Thermal Load" and "Environmental Impact Categories" charts, the Cube shows the highest proportion at 38%, indicating that its design may lead to increased energy requirements for thermal management, which in turn escalates its overall environmental footprint. This suggests that improvements in the Cube's thermal performance could potentially reduce its broader environmental impacts significantly.

Conversely, the Sphere, with the lowest share at 27% in both charts, demonstrates superior thermal efficiency, which correlates with a reduced environmental impact. This efficiency likely results from the Sphere's geometrical properties, which may include a minimized surface area exposed to external environmental conditions, leading to lower energy consumption for heating or cooling.

The Cask, occupying an intermediate position at 35% in both charts, reflects a moderate balance in terms of thermal and environmental performance. This indicates that while not as efficient as the Sphere, the Cask still presents opportunities for enhancement in design to reduce both thermal load and environmental impacts (Diagram 5.1).

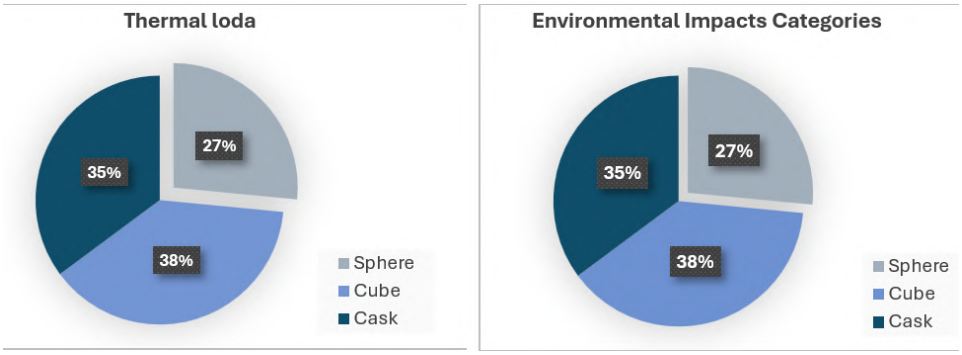


Diagram 5-2: comparison different geometries, Appendix C, Page437

The results generally indicate that, as a form for large office buildings in Boston, the sphere demonstrates superior performance compared to the cube and cask. The cask outperforms the cube. These findings support the research's initial hypothesis.

The comparative analysis of energy consumption between heating and cooling in the geometrical forms of Sphere, Cube, and Cask reveals a predominant energy expenditure towards heating, which accounts for 96% of the total thermal load in each geometry. Cooling, conversely, constitutes only 4% of the energy use. This significant disparity highlights the greater impact of heating on the overall energy profile of these structures, underscoring its importance in the design of energy systems for large office buildings in Boston (Diagram 5.2).

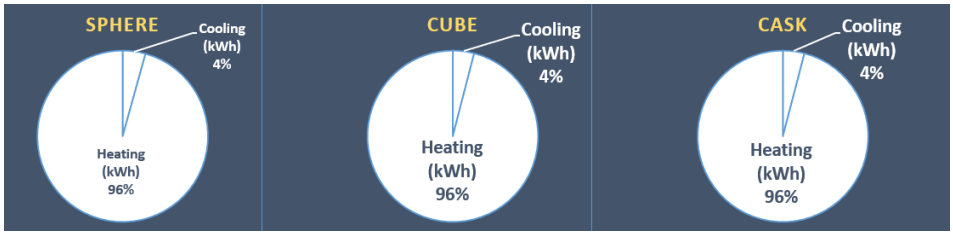


Diagram 5-5: comparison Heating and Cooling energy usage, Appendix C, Page 437

5.3.2.2 Normalization of the environmental impacts based on CO_2 eq

In discussing the normalization of environmental impact data, it is essential to distinguish between the normalization process and the expression of impacts in CO_2 equivalents. Normalization, as defined in ISO 14040 and ISO 14044, involves scaling environmental impacts relative to reference values derived from a standard dataset. This process helps to quantify and compare the significance of different environmental impacts within a common framework. The results of this normalization are then expressed in equivalent kilograms of CO_2 to provide a uniform scale for comparison, thereby facilitating a more straightforward communication of environmental performance. This step does not convert the impacts into CO_2 but uses CO_2 equivalents as a common metric for expressing the normalized results.

The normalization of environmental impact data into CO_2 equivalents facilitates the comparison of various impacts to global warming effects. This process, utilizing normalization factors derived from the US 2008 inventory data via tools such as openLCA and ecoivent 3.6, assigns specific values to each impact category. For instance, acidification is measured at 94.5501751778371, while carcinogenic impacts are rated at a mere 4.97525060101256E-5. Other categories like ecotoxicity and fossil fuel depletion are quantified at 10975.0810784115 and 21286.9221664978 respectively, with global warming itself normalized at 24038.981612583. The significant normalized CO_2 equivalent for fossil fuel depletion, which is 2.409 times greater than that of global warming, underscores a critical environmental issue. With an actual environmental impact recorded as 0.497635 MJ surplus in this category, the data points to the substantial environmental ramifications of continued reliance on non-renewable energy resources, emphasizing the pressing need to mitigate their CO_2 emissions (Diagram 5.3).

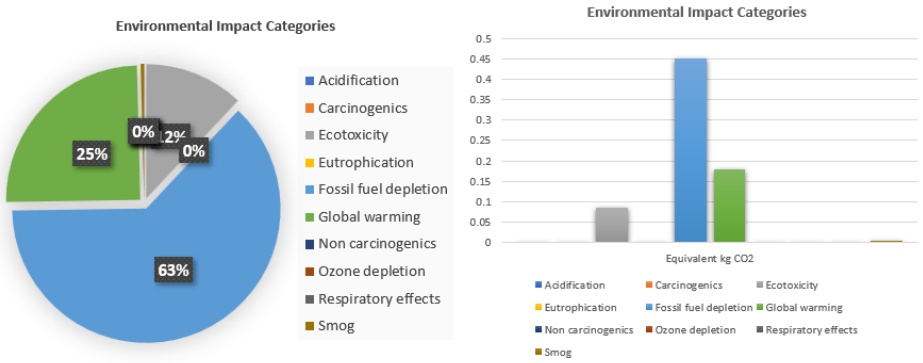


Diagram 5-8: comparison different environmental impact categories, Appendix C, Page 437

5.3.3 Analyzing the Effects of Changing Dimensions in Each Geometry

The final step of this section, aimed at addressing Main Question 2, involved conducting a detailed sensitivity analysis of the output data related to environmental impact categories. This analysis was crucial for evaluating how variations in input data, including specific variables, influenced the results. The objective was to identify which variables had the most significant impact on the outputs, essentially assessing the outputs' susceptibility to changes in these variables. Such an analysis is instrumental for designers to make informed decisions about dimension selection during the design phase. For this purpose, Python was selected as the appropriate software tool, offering the capability to analyze the data using a variety of algorithms.

5.3.3.1 Sphere

The sensitivity analysis of the sphere's output data demonstrates a pervasive and substantial impact of radial variations on the environmental parameters under study. stated the analysis in Chapter 4, The remarkably consistent strength of this relationship, with correlation coefficients consistently exceeding 0.97 across a diverse range of environmental impacts, is particularly significant. These results indicate that modifications to the radius of a spherical object will exert a predictable and considerable influence on these environmental metrics. These findings have profound theoretical implications, emphasizing the radius as a fundamental variable in environmental impact assessments of spherical structures. Across diverse applications, including architectural planning, and environmental policy formulation, the radius should be recognized as a crucial parameter with the potential to significantly modulate sustainability outcomes (figure 5-3).

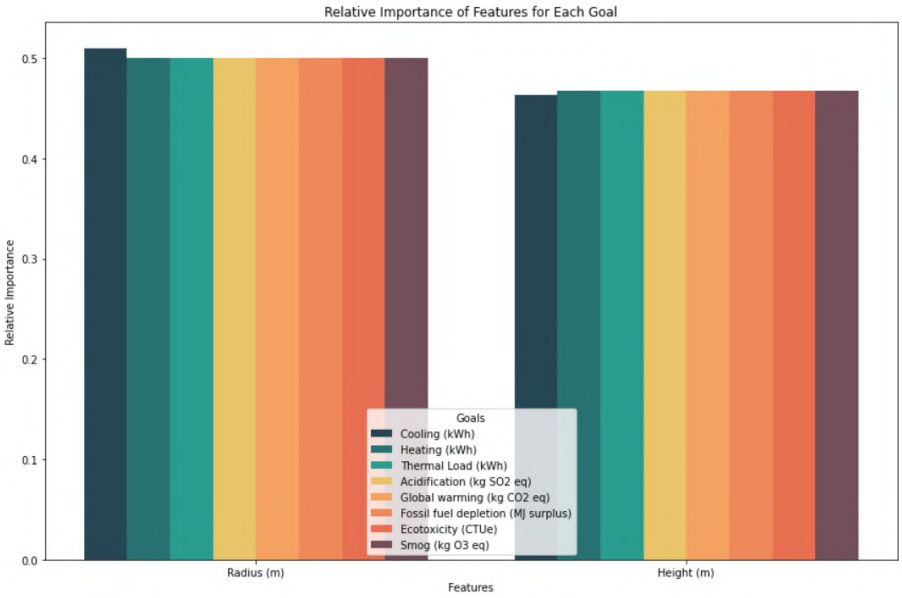


Figure 5-7: Relative Importance of Features for each goal (Sphere)

5.3.3.2 Cask

Figure 5-4 presents the results of a sensitivity analysis of Cask geometry assessing the relative influence of radius, height, and length on a variety of environmental objectives. The analysis establishes a clear hierarchy, with radius consistently demonstrating a greater impact on environmental outcomes than either height or length. This dominance is visually evident across multiple goals (including CO_2 reduction and energy savings), as reflected in the consistently higher bars associated with the radius variable. This diagram underscores the critical role of radius in determining the environmental impact of the cask and provides actionable insights for ecologically minded design optimization.

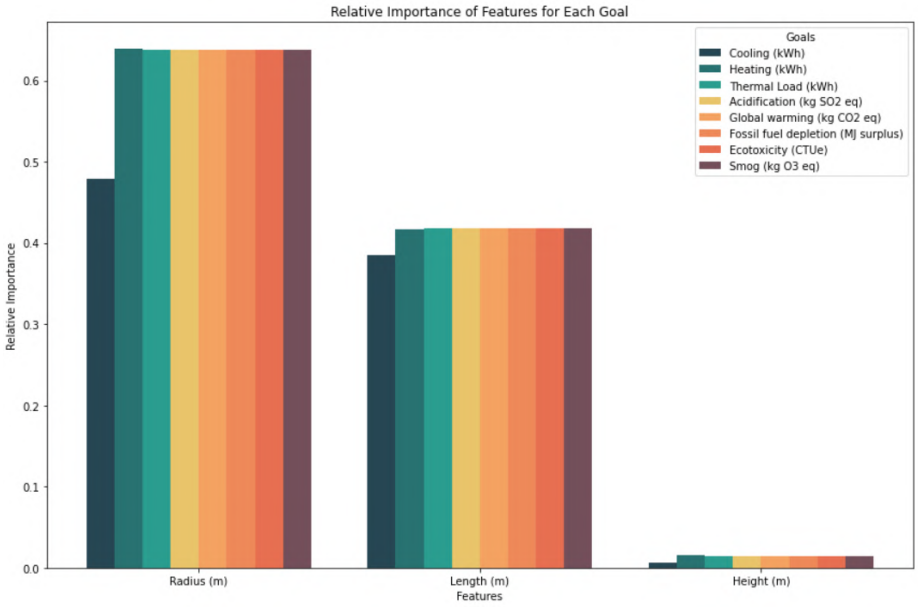


Figure 5-10: Relative Importance of Features for Each Goal (Cask)

5.3.3.3 Cube

Figure 5-5 reveals the results of a sensitivity analysis performed on a cubic structure. It demonstrates that the length dimension exerts a greater overall influence on output factors compared to width, particularly in metrics related to cooling. This finding aligns with the case study's Boston context, where longitudinal expansion may increase surface area and thus affect thermal regulation. The width dimension's significant impact on cooling performance could be explained by its influence on the building's aspect ratio, a key determinant of thermal behavior due to its effect on shading and solar exposure. Considering the length dimension's dominance across the majority of outputs, it emerges as the most influential factor within the specific climatic conditions of Boston.

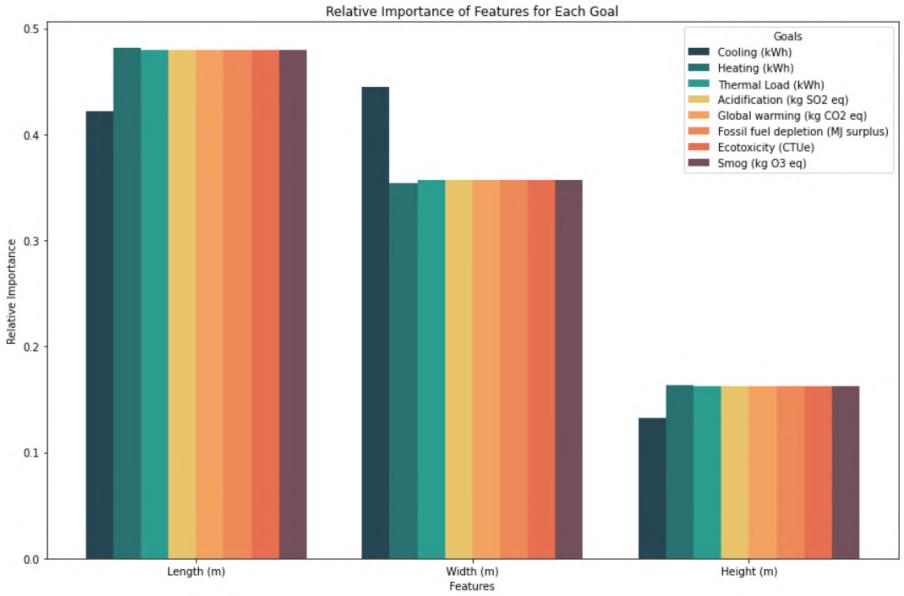


Figure 5-13: Sensitivity analysis of cube

5.3.4 Research questions and answers (first section results)

This research commenced with two overarching questions aimed at achieving corresponding goals. To enhance clarity and derive more actionable inquiries, each broad question was subdivided into two main questions. Further refinement led to the development of specific sub-questions for each main question, facilitating a more targeted approach to investigation.

The methodology followed a structured approach, beginning with the resolution of sub-questions. Insights gained from these initial analyses informed the answers to the main questions. Subsequently, the synthesis of these responses provided comprehensive solutions to the general questions. This iterative process ensured a thorough exploration and understanding of each layer of inquiry.

Ultimately, this structured decomposition and subsequent integration of questions and answers allowed for a detailed examination and resolution of the issues about the "Geometry" section of this study. This methodical approach not only streamlined the research process but also enhanced the depth and applicability of the findings.

SUB Q1-1: How is it possible to assess the environmental impact of geometry?

Answer:

The methodology integrates several advanced techniques. One way to compare the effects of geometry is by calculating the energy usage during the operation period (B6 stage), providing a direct measure of environmental impact. Firstly, parametric design is employed to systematically vary geometric dimensions and analyze their effects on environmental impacts. This approach allows for a comprehensive exploration of how different geometrical configurations influence environmental metrics. Secondly, normalization procedures are applied to the results to convert diverse environmental impact measures into a common unit, typically equivalent to kilograms of CO_2, facilitating a more straightforward comparison between different scenarios and geometric forms. Finally, Python, a versatile programming language, is utilized to compute sensitivity analyses. This involves assessing how changes in input parameters (such as dimensions and materials) affect the environmental outcomes.

SUB Q1-2: Which software is the best to investigate the environmental impact of geometry?

Answer:

This research explores various software options that are employed to calculate environmental impacts, including OpenLCA, OneClick LCA, and Athena. Among these options, OpenLCA and OneClick LCA emerged as superior choices due to their capability to integrate as plugins within Grasshopper, thus enhancing their utility in parametric design environments. Notably, the OpenLCA plugin for Rhino, known as Tortuga, facilitates seamless integration, providing robust support for environmental impact analysis within the design workflow. However, this study ultimately employed OpenLCA for its extensive ecoinvent database access and the availability of numerous predefined processes. This combination of comprehensive data coverage and functional integration into existing design tools underlines OpenLCA's effectiveness in conducting detailed environmental impact assessments aligned with the geometric specifications of the research.

SUB Q1-3: The biggest impact of geometry on environmental consequences may be found in which category?

Answer:

The research systematically evaluates the environmental impacts of different geometrical configurations through a normalization process. This analysis reveals that the four most significant environmental categories impacted by geometry include Fossil Fuel Depletion, Global Warming, Ecotoxicity, and Smog. Notably, Fossil Fuel Depletion emerges as the category with the highest CO_2 equivalence, registering at 0.4518289 kg. This finding underscores the substantial influence of geometric decisions on the consumption and depletion of non-renewable energy resources, positioning Fossil Fuel Depletion as the primary environmental concern in the context of geometrical design and its environmental implications.

Main Question 1: How do different geometric configurations affect the environmental performance of buildings in a specific climate?

Answer:

This research delves into the architectural aspects of building geometries and their direct environmental impact, particularly focusing on energy consumption during the operational phase (B6 stage). It emphasizes the importance of aligning geometric configurations with climatic features to enhance environmental performance. By investigating three distinct geometric designs, the study quantifies the energy usage in kilowatt-hours and assesses the environmental implications of producing and transmitting low-voltage electricity in a specific urban setting, such as Boston. This approach not only highlights the critical role of geometry in minimizing energy consumption but also illustrates how thoughtful architectural design can serve as a passive solution to environmental challenges. The findings provide a clear indication of how geometric variations can significantly affect a building's environmental footprint, reinforcing the necessity of integrating climatic considerations in the early stages of architectural design.

Sub Q2-1: How is it possible to assess the environmental impact of changing the dimensions of the Form?

Answer:

To assess the environmental impact of varying the dimensions of architectural forms, this research employed a parametric design methodology, focusing on three primary geometric shapes: the cask, cube, and sphere. Each geometry was subjected to variations in its dimensions—width, length, and height for the cube; radius and height for the sphere; and radius, height, and length for the cask. The study systematically modeled over 2000 iterations per geometry to examine the effects of these dimensional changes on thermal loads and environmental impact categories. A comprehensive sensitivity analysis was conducted to determine the influence of each variable on the defined outputs. This involved setting the varied dimensions as input data and the resulting thermal loads and environmental impact categories as output data. The analysis was executed using Python, which facilitated the evaluation of how modifications in each dimension impacted the environmental outcomes. The results from this analysis provided critical insights into which dimensions most significantly affect environmental performance, highlighting the importance of considering these factors in architectural design. By understanding the long-term environmental effects of specific geometric variations, designers can make more informed decisions to optimize the sustainability of their projects. This approach not only enhances the precision of environmental impact assessments but also reinforces the importance of integrating detailed geometrical analysis in the early stages of design to achieve better environmental outcomes.

Sub Q2-2: Which software can be used to investigate the environmental impact of changing the dimension of Forms a parametric variety?

Answer:

To determine the practical software for investigating the environmental impact of changing dimensions in parametric forms, this research utilized Rhino and Grasshopper to design parametric models. The integration of Honeybee and Ladybug within this software framework enabled the precise definition of climatic features, enhancing the

contextual relevance of the designs. Additionally, OpenLCA was employed to calculate the environmental impacts of the varying geometries, providing a robust framework for comprehensive environmental assessment.

For the sensitivity analysis, Python was utilized to conduct various analytical techniques including heat maps, Spearman, and Pearson correlations, SHAP (Shapley Additive exPlanations) diagrams, Fourier Response Functions (FRF), and XGBoost modeling. These methods were applied to each geometry to identify which variations are most critical and should be prioritized in the early stages of design. This combination of software tools and analytical techniques provides a powerful and versatile environment for environmental impact analysis in architectural design, allowing for detailed and targeted investigation into how changes in form dimensions affect sustainability metrics.

Sub Q2-3: Which geometric dimension has the greatest influence on a building's environmental impact?

Answer:

To ascertain which geometric dimension exerts the greatest influence on a building's environmental impact, this research conducted a detailed sensitivity analysis across different shapes: spheres, casks, and cubes. The findings indicate that for spheres, the radius is the most critical dimension, impacting environmental output measures more significantly than height. In the case of casks, changes in radius again showed a higher sensitivity in the output data compared to changes in length and height. For cubes, alterations in length were found to have a more pronounced effect on environmental metrics than changes in width or height. These results highlight the varying degrees of sensitivity of different geometric dimensions to environmental impacts, emphasizing the importance of prioritizing certain dimensions in the design process to optimize environmental performance. This nuanced understanding aids architects and designers in making informed decisions that can significantly reduce the ecological footprint of their constructions.

Main Question2: In building design, does changing geometric dimensions while maintaining equal volume result in a different environmental impact?

Answer:

In response to the query about whether changing geometric dimensions, while maintaining equal volume, impacts environmental outcomes differently, this study utilized sensitivity analysis to investigate the effect of various geometric variations on output data, including thermal load and environmental impacts. The findings reveal that both the thermal load and its subsequent environmental consequences during the B6 stages are directly influenced by these variations. Therefore, possessing knowledge about the optimal direction to extend or modify a geometry is crucial for enhancing the environmental performance of buildings. This insight underscores the importance of strategic geometric manipulation in architectural design to achieve more environmentally friendly structures, highlighting that mere volume consistency does not equate to uniform environmental impact. This research contributes to a more nuanced understanding of how geometric flexibility can be leveraged to reduce a building's ecological footprint.

General Questions 1: How does the deliberate selection of geometric forms reduce the environmental impact of buildings?
Answer:

The findings underscore the importance of considering geometric design in architectural projects not only for its direct impact on thermal efficiency but also for its broader environmental implications. Deliberate selection of geometric forms significantly impacts energy usage during the operational period, which in turn affects overall environmental consequences. Understanding the optimal directions for extending and enlarging geometries can directly influence these environmental outcomes, as evidenced by this study. Optimizing the thermal performance of buildings can directly contribute to more sustainable environmental outcomes, highlighting the critical role of design choices in building sustainability. In addition, the results underscore the critical importance of optimizing heating systems in the design of large office spaces in Boston to reduce overall energy consumption. The uniformity in the distribution of heating and cooling percentages across all three geometrical configurations indicates that thermal load management strategies should primarily focus on enhancing heating efficiency. Such a focus could potentially yield substantial reductions in energy consumption and associated environmental impacts.

Given the dominant role of heating in the total energy profile, strategies focused on enhancing heating efficiency could yield substantial reductions in energy use and associated environmental impacts. Therefore, prioritizing the improvement of heating systems should be considered a key design objective to achieve greater energy efficiency and sustainability in building management.

This analysis not only informs about specific energy use patterns but also guides the prioritization of energy efficiency measures, making it clear that heating system upgrades could provide the most significant leverage for energy savings in large office environments within this climatic context.

5.4 Key findings of Section2

5.4.1 Hypothesis and goals in Section 2

The second section of the thesis examines the environmental impacts of building cladding systems, specifically conducting a comparative analysis among aluminum, polycarbonate, and hybrid cladding systems. At the core of this analysis was the hypothesis that strategically combining different cladding materials could significantly improve the sustainability of buildings during the operational phase. The objective was to assess whether such a hybrid system could enhance environmental performance and sustainability more effectively than single-material systems, by leveraging the complementary properties of both aluminum and polycarbonate. To this end, the research initially explored the impact of material claddings on the environment by analyzing their effects on thermal load and subsequent environmental impacts throughout the operational phase of a building. Subsequently, the results from each material configuration were compared to evaluate the hypothesis. The findings confirm the hypothesis, demonstrating that the hybrid cladding system achieves the general goals of enhanced sustainability and reduced environmental impact. Such an analysis

is essential for understanding how different cladding materials contribute to overall building sustainability and for identifying which material configuration offers the most significant environmental advantages. This research not only aimed to validate the stated hypothesis but also to provide actionable insights that could guide future architectural decisions in the selection and integration of cladding materials to optimize environmental performance. Therefore, this section of the thesis makes a substantial contribution to the field of sustainable architecture by highlighting effective strategies to minimize the ecological footprint of buildings through thoughtful material selection and innovative system design. The subsequent sections will provide a summary of the hypotheses tested and the goals achieved (Figure 5.6).

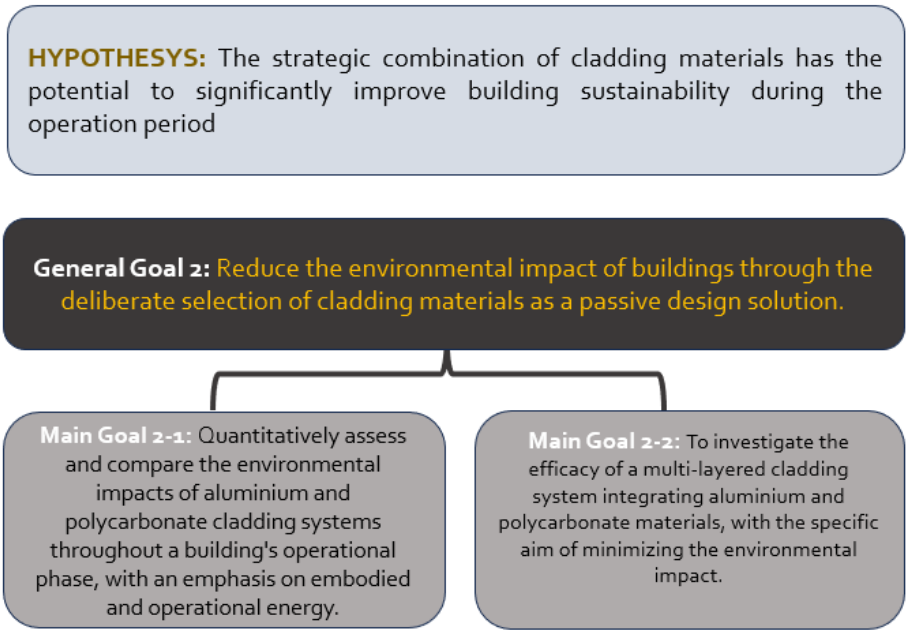


Figure 5-15: The research goals in section 2

5.4.2 Exploring Material's Impact: The Methodological Approaches in Section 2

In this section, the analysis focuses on optimizing the geometric model previously identified (spherical model introduced in Section One). To reach the general goal, this study aims to address the overarching question: How can strategic choices in cladding materials minimize the environmental impact of buildings?

The case study centers on a prototype representing a large office building tailored to the climatic conditions of Boston. To maintain analytical consistency, the dimensions of the model are held constant. The investigation explores how material properties influence the environmental performance of the building. Employing Rhino and Grasshopper plugins, the study examines two cladding systems: aluminum and polycarbonate. Key variables analyzed for each system include thickness, layering, and physical attributes. These materials were selected based on their presence in Environmental Product Declaration (EPD) libraries, which provide detailed information on the environmental impacts associated with the materials during their manufacturing (A) and end-of-life (C) stages. However, this research primarily focuses on the operational phase (B6 stage), evaluating how the chosen cladding systems influence

the building's environmental impact during operation. After conducting an initial environmental impact assessment, the study performs a comparative analysis between the aluminum and polycarbonate cladding systems. This is followed by the modeling of a combined cladding system that integrates both materials. An optimized model was developed through an extensive analysis involving 1,104,150,528 iterations, selected for its minimized environmental impact during the operational phase. This model was further evaluated against criteria such as Annual Sunlight Exposure (ASE) and Spatial Daylight Autonomy (SDA) to enhance sustainable building design and thermal load in B6 stage. The optimization was conducted using the Wallacei component in Rhino, which analyzed 7500 models and identified the 30 most optimized configurations. Subsequently, the data was imported into Design Explorer twice: first, the data from Wallacei, and then the output data from Ladybug. This systematic approach facilitated a thorough examination of the models to enhance the architectural design process. The optimized hybrid model, which incorporates the benefits of both aluminum and polycarbonate cladding, is compared with the single-material systems to assess its enhanced sustainability attributes during the operational phase. This evaluation was pivotal in determining the optimization and sustainability of the hybrid cladding system. The methodology of this research is methodically divided into three phases: initial analysis using an aluminum cladding system, followed by an analysis using a polycarbonate system, and concluding with an examination of a hybrid system that combines both materials. Upon analyzing the results, principles for designing spatial structures for large office buildings in Boston were developed.

5.4.2.1 Comparison Different Cladding systems (Aluminum and Polycarbonate)

In this section, the sphere was identified as the most appropriate geometric form based on the findings from Chapter 4. To isolate the variables and eliminate the effects of surface area and volume on the environmental impact, both parameters were held constant.

Overall area of the sphere=758.86 square meter

Sphere diameter = 31.4 meter

The total surface area encompassing all sides of the sphere=1519.60 square meters

Initially, a comparative analysis was conducted between aluminum and polycarbonate cladding systems. This analysis, rooted in the investigations and calculations detailed in Chapter 4, presented the following results, highlighting the optimized models in both materials (Table 5.2).

Table 5-5: optimized model of polycarbonate and aluminum cladding systems, Appendix D, Page 468

	out: Cooling (kWh)	out: Heating (kWh)	out: Lighting (kWh)	out: Total (kWh)
Aluminum	2319.195606	46904.56263	18186.60133	67410.35956
polycarbonate	86561.65844	242631.4407	6150.060827	335343.16

The analysis reveals that the polycarbonate cladding system results in significantly higher energy consumption during the operational phase compared to the aluminum system. Specifically, polycarbonate consumes 93.3% more energy for cooling and 80.7% more for heating than its aluminum counterpart. In contrast, the only aspect where aluminum cladding demonstrates superior energy efficiency is in lighting, where it uses 66.19% less energy than polycarbonate. Overall, the aluminum cladding system exhibits considerably lower energy consumption—79.9% less during the usage period—indicating markedly better performance (Diagram 5.4).

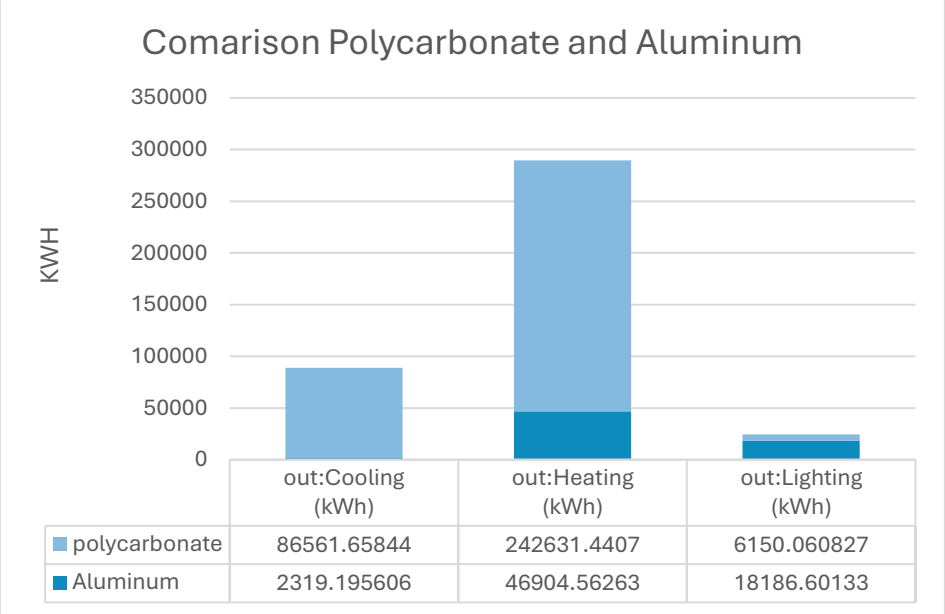


Diagram 5-11: Comparison Polycarbonate and Aluminum cladding system, Appendix C, Page 438

This differential in energy usage substantially influences the environmental impact of the building, underscoring aluminum's advantage in terms of sustainability. The following sections will detail the specific environmental impacts associated with these findings (table 5.3).

Table 5-8: Environmental Impact of different cladding systems, Appendix D, Page 468

	AC	CA	ECO	EUT	FFD	GW	NC	OD	RE	S
Aluminum	27.7415875	1.20E-04	13527.72	9.030089536	33545.78	15722.83	5.29E-04	1.96E-03	3.34E+00	344.7553
Polycarbonate	138.0047767	5.96E-04	67295.69	4.49E+01	166878.6	78215.6	2.63E-03	9.77E-03	1.66E+01	1.72E+03

The results indicate that the aluminum cladding system generally causes 79.9% less environmental impact compared to the polycarbonate system. To enhance the performance of each system, the analysis assessed the contributions of heating, cooling, and lighting to the overall environmental impact. This evaluation aimed to identify which component is responsible for the highest energy consumption and, consequently, the most significant environmental impacts.

The findings show that in the output data (thermal load and environmental impacts), lighting accounts for 2%, cooling for 26%, and heating for 72% of the impacts in the polycarbonate system. In comparison, for the aluminum cladding system, lighting constitutes 3%, cooling 27%, and heating 70% of the environmental impacts during the operational period. These results suggest that in both systems, developing strategies

to reduce energy consumption from heating in large office buildings is crucial for improving sustainability (Diagram 5-5).

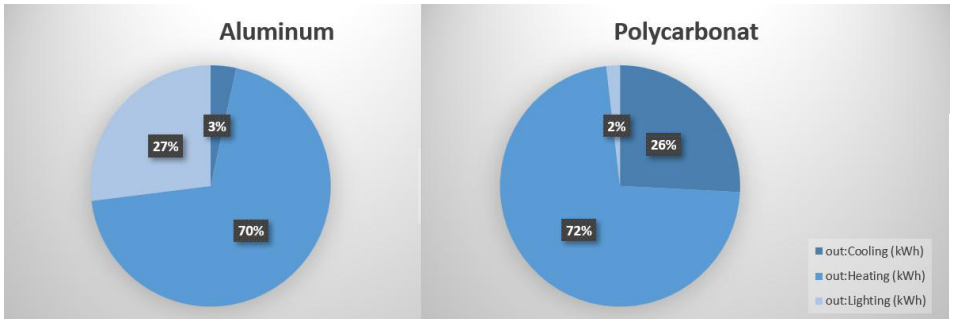
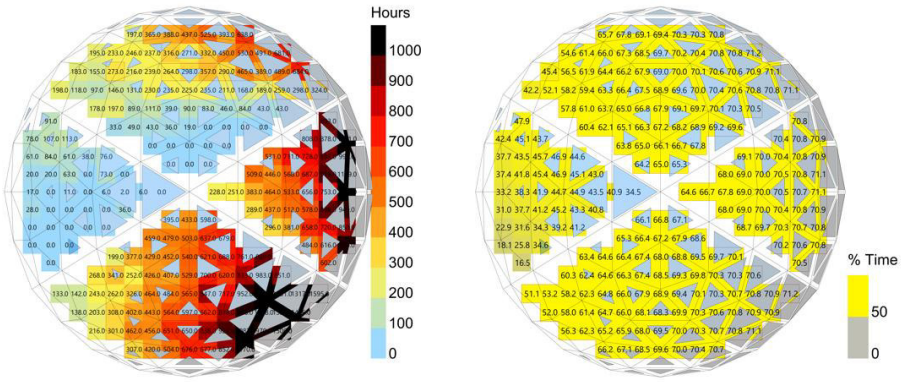


Diagram 5-14: Comparison the impact of lighting, heating and cooling energy usage, Appendix C, Page 438

Since the research aims to establish architectural principles for creating positive buildings, one method to evaluate the sustainability of buildings is through LEED certification. However, assessing sustainability solely based on thermal load is insufficient. Therefore, multiple factors need consideration. Cladding, for instance, influences the proportion of openings which in turn affects metrics such as Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE). These elements are critical as they allow for the regulation of openings beyond just managing the thermal load.

Given these considerations—thermal load, the proportion of openings, sDA, and ASE—both aluminum and polycarbonate systems, as illustrated in Figure 5-7 and 5-8, failed to meet LEED certification requirements. This failure primarily stems from deficiencies in utilizing daylight effectively, indicating a need for improved lighting strategies within these systems. Consequently, the next phase of research involves modeling a hybrid cladding system, designed to enhance performance across these parameters and potentially achieve better LEED certification outcomes.



ASE > 250/10%
55.4%
You have Failed LEED.

sDA 400/50%
74.3%
You have Passed LEED!

Figure 5-18: single polycarbonate Cladding systems

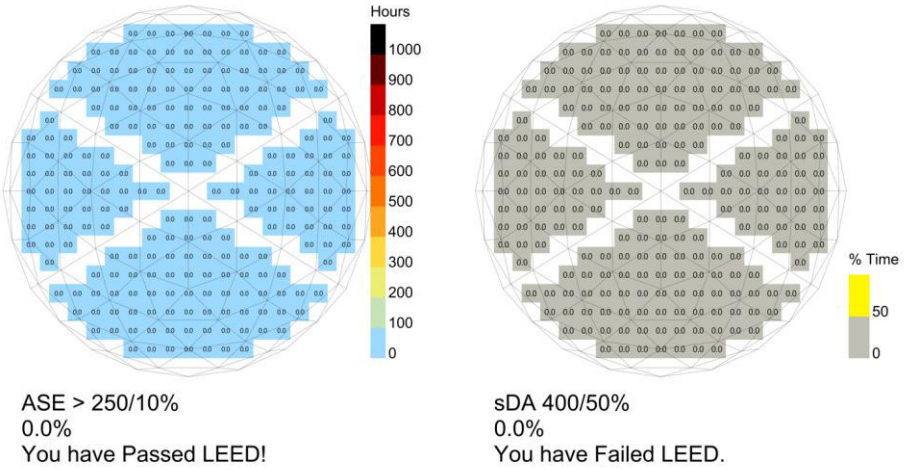


Figure 5-21: single Aluminum cladding system

In the initial settings, the criteria for Spatial Daylight Autonomy (sDA) was established at greater than 50%, and for Annual Sunlight Exposure (ASE) at less than 10%, in order to meet LEED standards. According to the analysis presented in the diagram, the polycarbonate cladding system achieved an sDA of 74.3%, indicating satisfactory performance in terms of daylight autonomy. However, it failed to meet the ASE criteria. Conversely, the Aluminum cladding system met the ASE requirement by maintaining exposure below the threshold but failed to achieve the required sDA percentage. These results indicate that, although the aluminum cladding systems exhibit favorable thermal performance, neither cladding system is suitable for the case study as both fail to fully comply with the LEED standards. Consequently, a hybrid cladding system combining these materials was subsequently modeled to explore the potential for meeting both sDA and ASE criteria.

5.4.3 Optimization (Method, result, and interpretation)

Optimization was conducted using the NSGA-2 algorithm, incorporating selection methods from the Wallacei plugin, such as Unsupervised Machine Learning, Parallel Coordinate, and Pareto Front. Through these methods, optimal choices have been selected.

This research not only aimed to control thermal load using varied proportions of aluminum and polycarbonate in the cladding system but also employed a method to manage daylighting to meet LEED standards for Annual Sunlight Exposure (ASE) and Spatial Daylight Autonomy (sDA). Specifically, the study recalibrated the distance from the sun, with values ranging from 0 to 0.9 (minimum: 0 to 0.35, maximum: 0.35 to 0.9). This recalibration was designed to determine the optimal percentage of aperture openings throughout the day in various geographic locations to comply with LEED standards. Additionally, the study carefully selected specific times and dates for data collection to make sure the information was applicable and reflected normal conditions typically experienced in those locations.The model was divided into four sections based on geographic orientation.

In order to enhance control over light absorption, the spatial structure was deliberately designed using parametric cells. This architectural approach allowed for precise

manipulation of the structural characteristics, facilitating the integration and customization of openings based on specific lighting requirements. The parametric design not only supported the efficient installation of these features but also enabled dynamic adjustments to the structure's interaction with light, thereby optimizing environmental performance and visual comfort within the space.
As explained in Chapter 4, the models were optimized using Wallacei, which selected 30 items from a total of 7,500 generations. Subsequently, a two-step optimization process was conducted using Design Explorer, which utilized data from both Wallacei and all output data from Ladybug. Table 2 presents the results from both optimization steps. The provided table 5-5details two optimized models, labeled TP 5 and TP 9, with various performance metrics assessed in relation to their cladding material compositions and their implications for energy efficiency and light management. (each material feature has been presented in chapter 4-26).

Figures 5-9 and 5-10 demonstrate that both models successfully meet LEED standards.

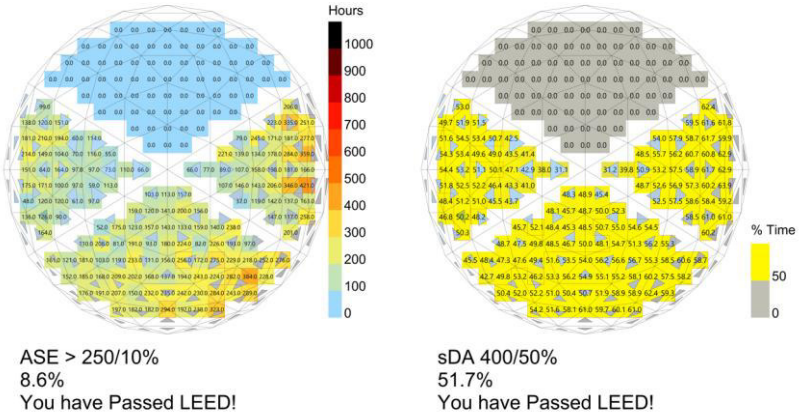


Figure 5-24: Model 5 analysis

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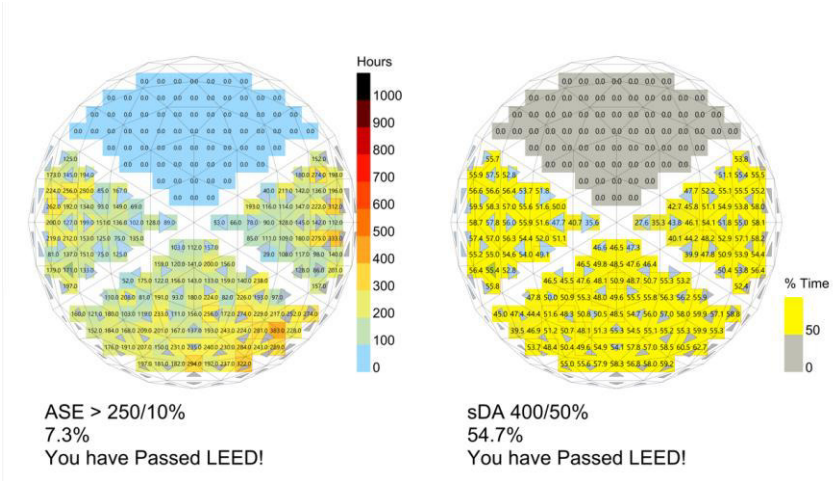


Figure 5-27: Model 9 analysis

The three bellow graphs provided depict the optimization of the hybrid cladding system based on three key performance indicators: Thermal Load, Spatial Daylight Autonomy (sDA), and Annual Sun Exposure (ASE). Each graph uses a standard deviation

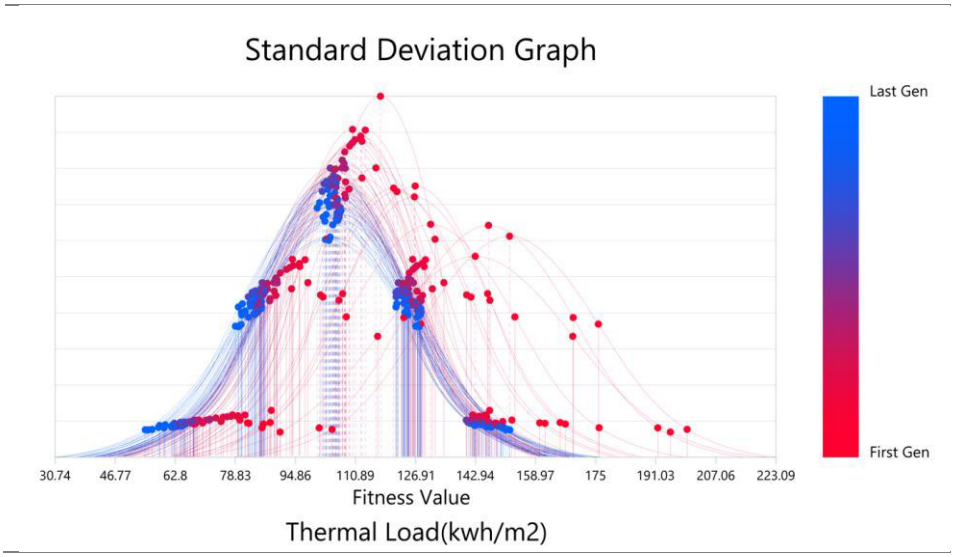
representation to show the distribution and progression of these values through various generations of an optimization algorithm.

5.4.3.1 Evaluating the Effectiveness of Optimization with Genetic Algorithms in Hybrid Cladding Systems

In the subsequent analysis, the success of the optimization was evaluated using statistical trendlines: the Standard Deviation Trendline and the Mean Values Trendline. These tools were employed to assess the efficacy of the optimization within the context of the research methodology, providing a quantitative measure of how well the optimization performed. This approach allows for a detailed examination of the variability and central tendency of the optimized outcomes, facilitating a comprehensive understanding of the effectiveness of the optimization strategies employed in the study.

5.4.3.1.1 Standard Deviation Trendline

Diagram 5.6 depicts the optimization of a hybrid cladding system based on three key performance indicators: Thermal Load, Spatial Daylight Autonomy (sDA), and Annual Sun Exposure (ASE). Each graph uses a standard deviation representation to show the distribution and progression of these values through various generations of an optimization algorithm.
The standard deviation represents the distribution of a set of values from the mean. A low standard deviation factor indicates that most values are clustered around the mean (less variation within the population), while a high standard deviation factor indicates that the values are spread out farther from the mean (more variation within the population). The aim of the chart is to present and analyse the levels of variation/convergence for each generation in the population, as well as whether the generations are getting fitter throughout the simulation. Increased variation is represented through a 'flat' curve, while increased convergence is represented through a 'narrow' curve. A shift in the curve to the left indicates better mean performance.



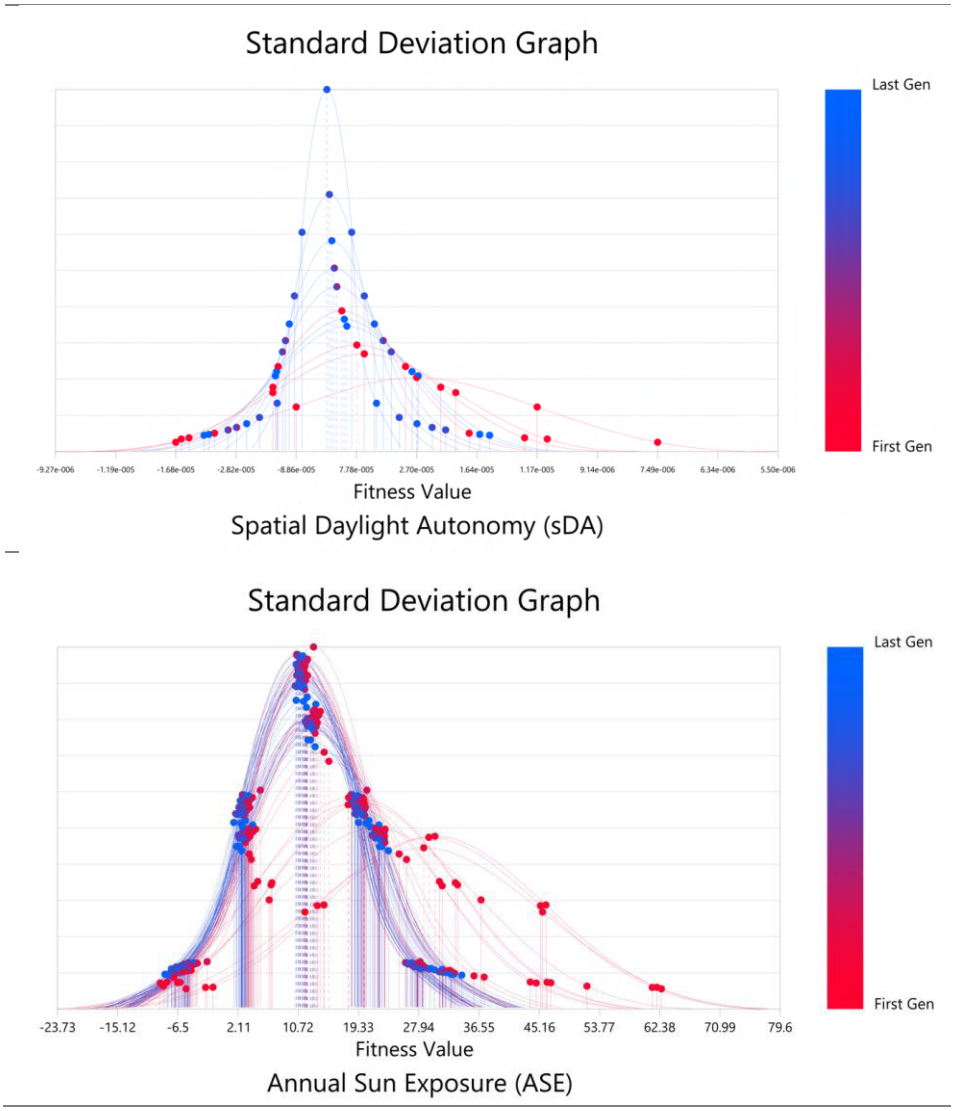


Diagram 5-17: Standard Deviation Graph, Appendix C, Page 439

Thermal Load Graph:
The x-axis represents the fitness value, and the y-axis represents thermal load (kWh/m²). The spread of the points indicates variability in the fitness values concerning the thermal load. Early generations (blue points) show a widespread, which narrows in later generations (red points), suggesting a convergence towards optimal solutions that minimize the thermal load while maintaining or improving fitness.

Spatial Daylight Autonomy (sDA) Graph:
This graph plots the fitness value against the sDA. The points are more tightly clustered, particularly in later generations, indicating a quicker convergence towards high sDA values. This suggests that optimizing for sDA within the hybrid cladding system was more straightforward or that effective solutions were reached earlier in the process.

Annual Sun Exposure (ASE) Graph:
The fitness values are plotted against ASE. Similar to the sDA graph, the convergence is notable in later generations but with a slightly more dispersed distribution than sDA,

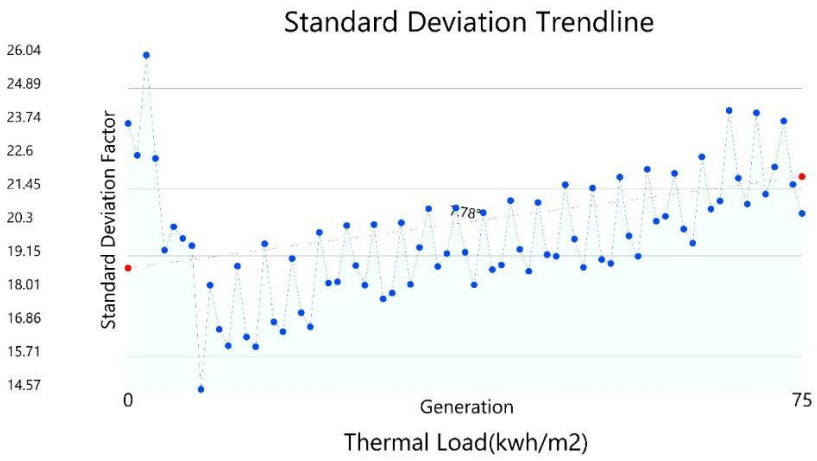
pointing to a balance between reducing sun exposure and achieving desired fitness levels.

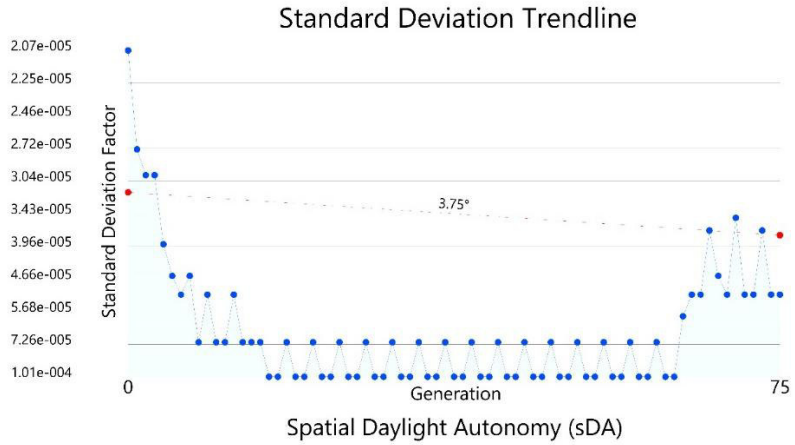
In general, the graphs demonstrate the standard deviation and convergence of values across generations during the optimization process. Early generations exhibit greater diversity in solutions, reflected in the wider dispersion of data points. As optimization progresses, the data points converge towards more optimal values, indicating that the solutions are stabilizing around a set of more effective configurations.
For instance, the sDA graph shows a relatively quick convergence, suggesting that achieving optimal daylight autonomy was less complex compared to managing thermal load and ASE. On the other hand, the Thermal Load graph shows a wider spread in earlier generations and a gradual narrowing, which indicates a more challenging optimization path, requiring more generations to find a balance between low thermal load and high fitness values.
The ASE graph highlights an intermediate level of challenge; it converges, but not as tightly as sDA, reflecting the complexity in balancing sun exposure with other architectural performance metrics.

Conclusion: The optimization of the hybrid cladding system effectively progresses as evidenced by the reduction in variability and stabilization of solutions in later generations across all three performance indicators. These graphs collectively illustrate the effectiveness of the optimization algorithm in homing in on solutions that balance thermal performance, daylight autonomy, and sun exposure, key factors in sustainable building design.

5.4.3.1.2 Standard Deviation Trendline

The provided trendline charts 5-7 represent the standard deviation of three performance metrics—Thermal Load, Spatial Daylight Autonomy (sDA), and Annual Sun Exposure (ASE)—across 75 generations of an optimization process. Each generation includes 100 genetic iterations, suggesting a comprehensive and robust analysis. The charts reveal insights into the convergence behavior and variability of solutions across successive generations (Diagram 5.7).





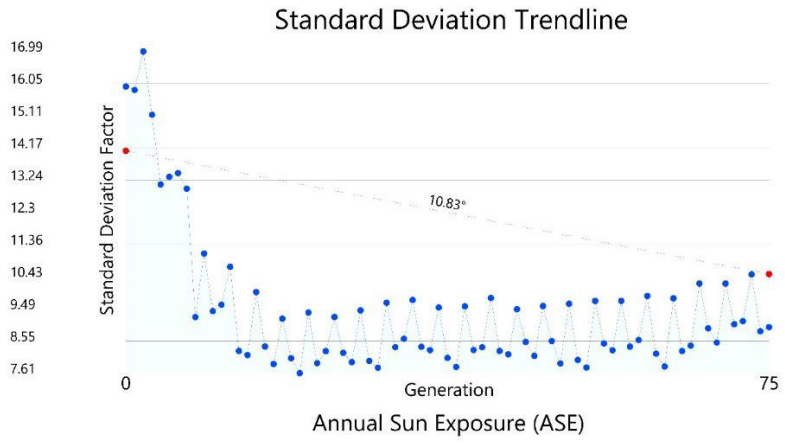


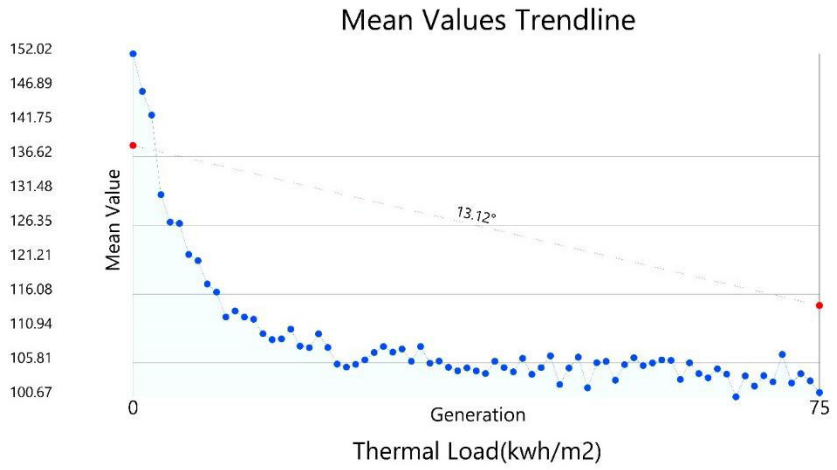
Diagram 5.7: Standard Deviation Trendline, Appendix page 440

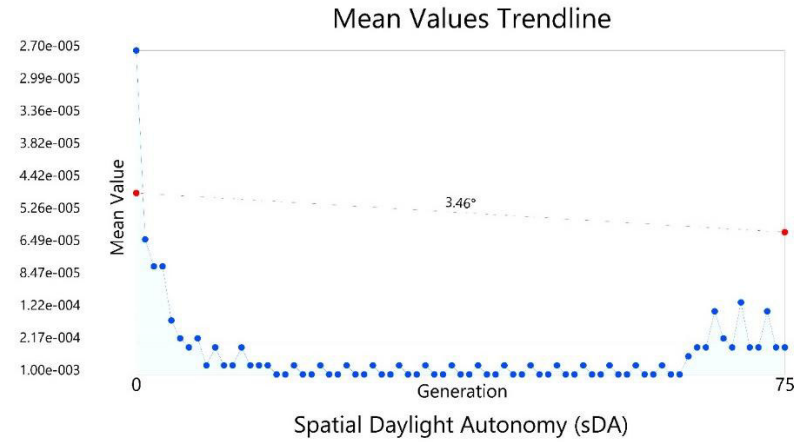
Thermal Load:
The trendline chart for Thermal Load shows a gradual decrease in the standard deviation as the generations progress. This reduction indicates a converging pattern where the range of solutions narrows, suggesting that the optimization algorithm is effectively homing in on the most efficient thermal performance configurations. The slight uptick towards the last generation might reflect a diversification strategy to explore slightly varied solutions that might yield better overall system performance.
Spatial Daylight Autonomy (sDA):
The sDA chart presents an initial sharp decline in standard deviation, which stabilizes relatively early in the process. This rapid convergence suggests that optimal solutions for maximizing daylight autonomy were identified quickly and consistently maintained throughout subsequent generations. The stability in sDA indicates that the parameter was less sensitive to the variations in the genetic configurations beyond a certain threshold.
Annual Sun Exposure (ASE):
The ASE chart depicts a pattern of consistent decline in standard deviation, indicative of gradual convergence towards a narrow range of effective solutions. This trend demonstrates the optimization algorithm's success in reducing unwanted sun exposure, a crucial factor in minimizing overheating and glare in building environments.

Conclusion: The analysis of the standard deviation across generations in these trendline charts highlights the effectiveness of the genetic algorithm in optimizing the hybrid cladding system across different environmental performance indicators. While the initial configurations exhibited a broad range of potential solutions, indicated by higher standard deviations, the algorithm progressively focused on more optimal configurations, particularly evident in the sDA and ASE metrics.
The convergence patterns in these charts are crucial for understanding how various solutions for the hybrid cladding system balance energy efficiency, daylight utilization, and sun exposure. These insights not only validate the robustness of the optimization process but also guide future iterations towards areas requiring further exploration or refinement. The overall trend towards lower standard deviations across all three metrics by the final generations underscores the potential to achieve a well-balanced, sustainable architectural design through systematic optimization.

5.4.3.1.3 Mean Values Trendline

The Mean Values Trendline charts for Thermal Load, Spatial Daylight Autonomy (sDA), and Annual Sun Exposure (ASE) across 75 generations offer a visual representation of how the average values of these metrics evolve during the optimization process. These charts provide a clear narrative on the progression and effectiveness of the optimization strategies employed (Diagram 5.8).





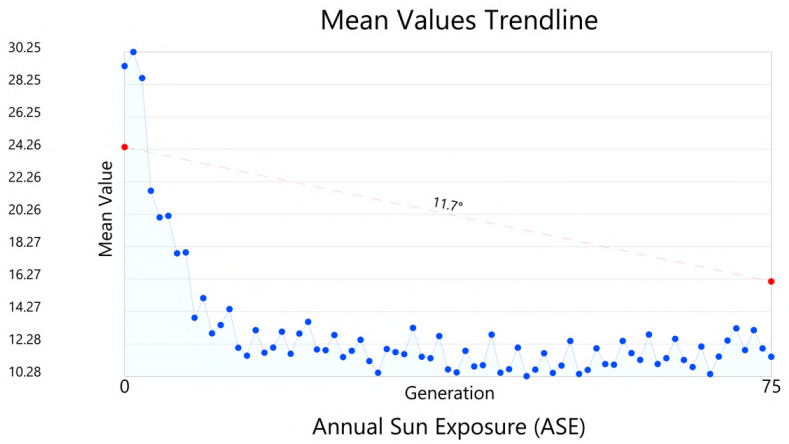


Diagram 5-23: Mean Values Trendline, Appendix C, Page 441

Thermal Load:
The trendline for Thermal Load displays a significant initial decline, followed by a steady decrease until it stabilizes towards the later generations. This pattern suggests that the optimization algorithm rapidly identified more efficient configurations that significantly reduced the thermal load, with incremental improvements as the generations progressed. The overall downward trajectory indicates successful optimization towards minimizing energy consumption related to thermal aspects.
Spatial Daylight Autonomy (sDA):
The sDA chart shows a sharp decrease at the outset, leveling off rapidly. This suggests that optimal solutions for sDA were quickly found and sustained throughout the remaining generations. The relatively flat trend after the initial drop indicates that once optimal daylight utilization configurations were established, further improvements were minimal, reflecting a successful early optimization.
Annual Sun Exposure (ASE):
The ASE chart also demonstrates a marked decline in the early generations with a gradual stabilization, which suggests that strategies to minimize undesirable sun exposure were effectively implemented early in the optimization process. The consistent mean values in later generations imply that the solutions were effective and required minimal adjustment thereafter.

Conclusion: The trendline analyses across the three metrics indicate a strong initial optimization phase, where significant improvements in thermal load, sDA, and ASE were achieved quickly. This was followed by a stabilization phase where mean values showed little variation, suggesting that the optimal solutions had been effectively integrated into the design configurations. The downward trend in all three metrics confirms that the optimization objectives—reducing thermal load and ASE while enhancing sDA—were successfully met.
These charts underscore the robustness of the optimization process in achieving sustainability goals in the architectural design of hybrid cladding systems. The early convergence to optimal solutions and the maintenance of these solutions across generations highlight the efficiency of the genetic algorithm used in this study. This analysis not only validates the effectiveness of the optimization but also provides a blueprint for future efforts to enhance building performance through similar methodologies.

5.4.3.2 Comparison of model 5 and model 9

Table 5-4 showcases two optimized models that conform to LEED standards through their strategic material use and energy management. Model 5, with its slightly higher ratios of aluminum and polycarbonate, demonstrates a marginal increase in cooling and heating demands but improved efficiency in lighting compared to Model 9. Despite these nuances in energy consumption, Model 9 is superior in optimizing daylight use and minimizing unwanted sunlight exposure, as evidenced by its higher sDA and lower ASE scores. These differences, although slight, highlight the impact of material composition and architectural design on the sustainability and energy efficiency of building envelopes. Both models illustrate effective strategies to balance thermal and lighting energy requirements while adhering to environmental standards.

TP	AL Ratio	PL Ratio	Cooling	Heating	Lighting	TL	sDA	ASE
5	93.18	6.83	13704.53	57379.51	8006.35	71084.04	51.42181	8.64
9	93.193	6.82	13689.41	57063.43	8017.657	70752.84	53.37888	7.325

Table 5-11: Optimized models feature, Appendix D, page 468

- TP (Test Point): The model number.
- AL Ratio: Percentage of the cladding composed of aluminum.
- PL Ratio: Percentage of the cladding composed of polycarbonate.
- Cooling, Heating, Lighting: These columns quantify energy consumption in kWh for cooling, heating, and lighting respectively.
- Total Energy: Summation of energy consumed across cooling, heating, and lighting.
- sDA (Spatial Daylight Autonomy): Indicates the percentage of time that sufficient daylight is available.
- ASE (Annual Sunlight Exposure): Measures the extent of area subjected to excessive sunlight, potentially leading to glare or thermal discomfort.

5.4.3.2.1 Material Composition:

Both models use almost similar ratios of materials with Model 5 using 93.18% aluminum and 6.82% polycarbonate, and Model 9 using 93.18% aluminum and 6.82% polycarbonate. This minor difference in polycarbonate ratio has a marginal effect on energy efficiencies.

5.4.3.2.2 Energy Consumption:

Cooling: Model 5 uses slightly more energy for cooling than Model 9. It is almost 0.11%.
Heating: Model 5 also consumes more heating compared to Model 9. It is Almost 0.55%.
Lighting: Conversely, Model 5 is slightly more efficient in lighting, using less energy than Model 9 . it is Almost 0.14 % less than model 9.
Total Energy: Model 5 has a higher total energy consumption compared to Model 9. almost 0.40 %

5.4.3.2.3 Daylight and Sunlight Metrics:

sDA: Model 9 achieves a higher sDA (53.38%) compared to Model 5 (51.42%), suggesting better daylight utilization.
ASE: Model 9 has a lower ASE (7.325) than Model 5 (8.64), indicating less exposure to excessive sunlight, which is advantageous in reducing glare and cooling demands.

Tables 5 . 5 and 5.6 illustrate the extent of polycarbonate surfaces used as Skylights in each cell in each direction for the optimized models. The area of these skylights varies with the angle of solar incidence and is adjusted within a specific range of surface areas to enable efficient control of daylight and improve interior lighting quality.

Table 5-14: Skylight Area in model 5.in each cell, Appendix D, Page468

Geographical direction (TP5)	North	East	Sout	West
Min Area **(m²)**	0	0.84	0.2	0.49
Max Area **(m²)**	0	1.65	1.23	1,71

Table 5-17: Sky lights Area in model 9 in each cell, Appendix D Page 469

Geographical direction (TP9)	North	East	Sout	West
Min Area **(m²)**	0	0.65	0.20	0.66
Max Area **(m²)**	0	1.28	1.24	1.71

5.4.3.3 Comparison of all cladding systems (Polycarbonate, Aluminum, Hybrid)

Ultimately, all cladding systems were compared in terms of total load (kWh), spatial daylight autonomy (sDA), and annual sunlight exposure (ASE) to elucidate the differences between the optimized model and the individual aluminum and polycarbonate systems. The results are presented in Table 5-7.

Table 5-20: Comparison 4 cladding systems, Appendix D, Page 469

Cladding systems	Cooling (kWh)	Heating (kWh)	Lighting (kWh)	Total (kWh)	sDA %	ASE %
Aluminum	2319.196	46904.57	18186.60	67410.36	0	0
polycarbonate	86561.658	242631.44	6150.06	335343.16	74.30	55.40
Hybrid Model 5	13704.528	57379.51	8006.35	79090.39	51.70	8.60
Hybrid model 9	13689.410	57063.43	8017.66	78770.50	54.70	7.3

Interpretation table 5-6:

Aluminum Cladding System: This system shows the lowest total energy consumption (67,410.36 kWh) among the evaluated systems, indicating efficient performance in terms of energy usage. However, it has zero percent in both spatial daylight autonomy (sDA) and annual sunlight exposure (ASE), suggesting poor natural light utilization. Despite its effective energy use, the lack of daylight penetration means this cladding system fails to meet LEED standards for indoor environmental quality, specifically in terms of daylight and views. Consequently, while the system is energy-efficient, it would not pass LEED certification due to inadequate daylighting performance.

Polycarbonate Cladding System: While this system exhibits the highest energy consumption at 335,343.16 kWh, it also shows strong performance in spatial daylight autonomy (sDA) with a 74.30% rating. However, its annual sunlight exposure (ASE) at 55.40% significantly exceeds the LEED requirement of less than 10%, which indicates a critical drawback in terms of excessive sunlight exposure. This high ASE value suggests that while the system allows for substantial natural light penetration, it also potentially leading to increased cooling and heating demands. Therefore, despite its benefits in enhancing daylight, the polycarbonate system fails to meet optimal standards for sustainable building design as specified by LEED guidelines.

Hybrid Model 5: As an optimized hybrid system, this model demonstrates balanced performance with a total energy consumption of 79,090.39 kWh. It achieves a moderate spatial daylight autonomy (sDA) of 51.70% and an annual sunlight exposure (ASE) of 8.60%, effectively balancing energy efficiency with daylight utilization. Importantly, its ASE value is well within the LEED requirement of less than 10%, and its sDA exceeds the 50% threshold, making it compliant with LEED standards for minimizing excessive sunlight exposure while ensuring sufficient natural light. This system exemplifies an effective integration of energy performance and daylight quality, thereby qualifying for LEED certification based on its optimized environmental credentials.

Hybrid Model 9: Like Hybrid Model 5, this model displays slightly lower total energy consumption at 78,770.50 kWh and achieves a slightly higher spatial daylight autonomy (sDA) of 54.70%. Its annual sunlight exposure (ASE) is lower, at 7.30%, indicating a nuanced variation in the optimization that favors daylight autonomy while further reducing sunlight exposure. These characteristics suggest a careful balance that enhances natural light utilization without compromising energy efficiency. The ASE well below the LEED threshold of 10% and the sDA exceeding 50% indicate that this system not only meets but also surpasses LEED requirements, reflecting its optimized design for sustainable building environments.
Diagram 5-9 provides a comparative visualization of various cladding systems, facilitating an analysis to determine which output is most critical for focused study.

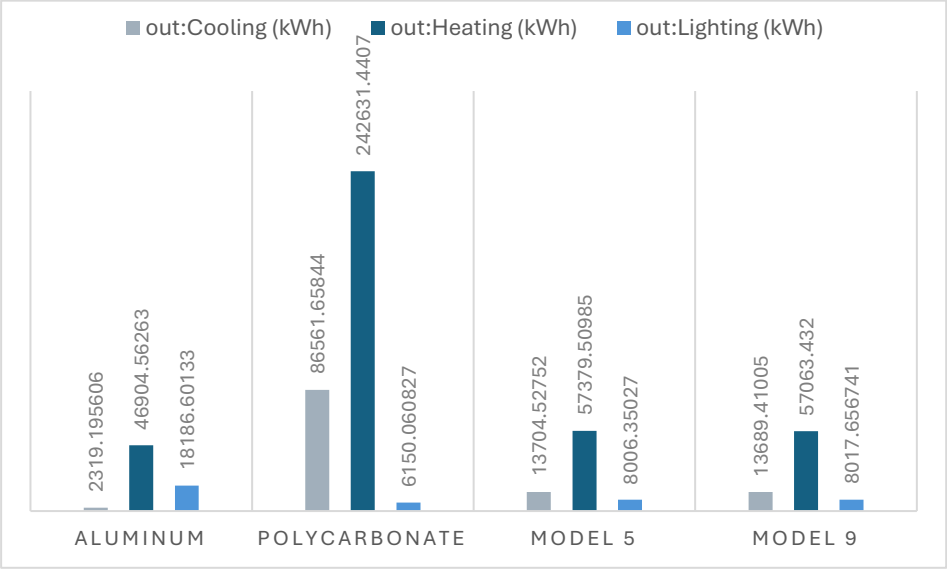


Diagram 5-26: Comparison different cladding systems, Appendix C, page 442

The results indicate that across all cladding systems, energy consumption for heating significantly exceeds that for cooling and lighting. This disparity suggests that developing strategies to enhance the thermal efficiency of cladding materials could lead to substantial reductions in overall energy use. Enhancing insulation properties and optimizing thermal mass could be potential avenues for reducing heating demands and improving the environmental sustainability of building designs.

5.4.3.3.1 Achievements in Section 2

The analysis indicates that the aluminum cladding system demonstrates more favorable overall energy usage compared to the optimized Model 9 across heating, cooling, and lighting. Model 9 consumes approximately 83% more energy for cooling and 17.8% more for heating than the aluminum system. However, it excels in lighting efficiency, using 126.8% less energy than its counterpart.
Generally, in terms of total energy usage, aluminum shows a 14.42% better performance in energy efficiency relative to Model 9. This directly impacts the environmental footprint, as shown in Table 5.8, where Model 9 has 14.42% more environmental impacts than the aluminum system.

Table 5-23: Comparison Environmental Impacts of different , cladding systems, Appendix D, page469

	AC[2]	CA	ECO	EUT	FFD	GW	NCA	OD	RE	S
Aluminum	27.7416	0.0001	13527.7157	9.0301	33545.7840	15722.8256	0.0005	0.0020	3.3351	344.7553
polycarbonate	138.0048	0.0006	67295.6942	44.9216	166878.6400	78215.6046	0.0026	0.0098	16.5912	1715.0378
Model 5	32.5483	0.0001	15871.6304	10.5947	39358.1820	18447.0817	0.0006	0.0023	3.9130	404.4902
model 9	32.4167	0.0001	15807.4354	10.5519	39198.9920	18372.4699	0.0006	0.0023	3.8972	402.8541

Although Model 9 meets LEED standards, its increased energy demands for cooling and heating underscore the critical need for solutions to reduce energy consumption, particularly in the cooling system. This emphasizes the importance of a balanced optimization strategy in cladding systems to enhance overall energy performance without disproportionately escalating specific energy requirements.
Table 5.9 displays the area of the lighting openings in each optimized model to meet LEED standards for Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE), and managing energy usage effectively.

Table 5-26: area of opening in each direction., Appendix D, page 469

	North (m^2)	East (m^2)	Sout (m^2)	West (m^2)
Model 5	0	36.37	37.98	29.33
Model 9	0	29.88	37.98	35.71

The results indicate that for a dome encompassing a surface area of 1,519 square meters, designated for large office functions in Boston, achieving LEED standards in Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) necessitates specific configurations of lighting openings. To effectively manage energy usage during the operational period, the architectural design includes zero square meters of lighting openings on the north side. In contrast, the eastern openings measure 36.37 square meters for Model 5 and 29.88 square meters for Model 9, the southern openings are consistent at 37.98 square meters for both models, and the western openings are 29.33 square meters for Model 5 and 35.71 square meters for Model 9. These dimensions are strategically designed to optimize both natural lighting and energy efficiency, adhering to the stringent requirements set forth by LEED certification standards.

2 TI (Thermal Load , kwh/m2), AC (Acidification, kg SO_2 eq), CA (Carcinogenic, CTUh), ECO (Ecotoxicity, CTUe), EUT (Eutrophication, kg N eq), FFD (Fossil fuel depletion, MJ surplus), GW (Global warming, kg CO_2 eq), NCA (Non carcinogenic, CTUh), OD (Ozone depletion, kg CFC-11 eq), RE (Respiratory effect, kg PM2.5 eq), S (Smog, kg O_3 eq)

5.4.4 Research question and answers (Second section results)

Like Section One, this part will address the research questions posed in Section Two. Detailed analyses and discussions will be presented to provide comprehensive answers based on the collected data.

SUB Q1-1: What is the difference in energy consumption between aluminum and polycarbonate cladding systems?

Answer:

The energy consumption data for aluminum and polycarbonate cladding systems reveals significant variances across different energy use categories. For cooling, aluminum consumes 2,319.20 kWh, which is only 2.68% of the 86,561.66 kWh consumed by polycarbonate, highlighting a drastic efficiency in favor of aluminum. In terms of heating, aluminum's consumption is 46,904.56 kWh, representing 19.33% of the heating energy used by polycarbonate, which consumes 242,631.44 kWh. Lighting shows a reversal in this trend where aluminum's consumption of 18,186.60 kWh is higher, constituting 295.83% of the 6,150.06-kWh used by polycarbonate. Overall, when considering the total energy consumption, aluminum's usage totals 67,410.36 kWh, approximately 20.10% of the 335,343.16-kWh consumed by the polycarbonate system. These comparisons underscore aluminum as a more energy-efficient option in terms of cooling and heating, but less so in lighting compared to polycarbonate.

A critical issue identified in both cladding systems is their substantial energy consumption for heating. Specifically, in the aluminum cladding system, heating accounts for 69.58% of the total energy usage, compared to 3.4% for cooling and 26.97% for lighting. Conversely, in the polycarbonate system, heating constitutes 72.35% of total energy use, with 25.81% dedicated to cooling and only 1.83% to lighting. These proportions underscore the dominant role of heating in the overall energy profile of both systems, indicating a significant area for potential energy optimization.

SUBQ1-2: How do the environmental impacts of aluminum and polycarbonate cladding systems compare?

Answer:
The analysis presented in Chapter 4 of this dissertation reveals significant differences in the environmental impacts of aluminum and polycarbonate cladding systems during the use phase of buildings. Specifically, the aluminum cladding system is associated with only 20.1% of the environmental impact attributed to the polycarbonate system, indicating substantially better performance in terms of minimizing adverse environmental effects during this phase. It is important to note that this research is confined to the use phase; therefore, comparisons of the environmental impacts of aluminum and polycarbonate during the manufacturing (A) and end-of-life (C) stages are beyond the scope of this study. These phases represent potential topics for future research, which could provide a more comprehensive understanding of the total lifecycle impacts of these materials.

SUBQ1-3: Which cladding system is more likely to achieve LEED certification?

Answer:

The evaluation of cladding systems' potential to achieve LEED certification necessitates a thorough understanding of their impact on both daylight autonomy and energy performance within the built environment. LEED certification emphasizes not only energy efficiency but also the quality of the indoor environment, which includes optimizing natural light. According to the LEED criteria, achieving certification requires a spatial daylight autonomy (sDA) of at least 50% and an annual sunlight exposure (ASE) of less than 10%.

In this context, the polycarbonate cladding system, despite its high sDA of 74.30%, significantly surpasses the desirable threshold for daylight autonomy, suggesting an effective use of natural light. However, its ASE of 55.40% far exceeds the LEED limit, indicating excessive sunlight exposure that could lead to glare and higher cooling loads, potentially negating some of its benefits in daylight utilization. Conversely, the aluminum system, with both an sDA and ASE of 0%, completely fails to utilize daylight, which is a crucial component of sustainable building design, particularly under LEED standards.

therfore while aluminum cladding demonstrates superior performance in terms of energy usage during the operational phase, this alone is insufficient for LEED certification, which requires a balanced approach to both energy efficiency and environmental quality.

This analysis suggests that neither system, in its current standard form, meets all the LEED requirements for daylight and energy performance, indicating a need for hybrid solutions or additional design interventions. Such solutions might include integrating adaptive shading systems with polycarbonate to control excessive sunlight exposure or enhancing aluminum systems with elements that increase daylight penetration without compromising thermal comfort.

Ultimately, the choice of cladding system should be guided by a comprehensive assessment of building function, location, orientation, and climatic conditions. These factors will determine the overall effectiveness of the material in contributing to a building's sustainability goals and its ability to meet stringent standards like those set by LEED. Therefore, focusing solely on one aspect, such as energy efficiency, without addressing daylight and comfort parameters, may not only hinder achieving LEED certification but also detract from the broader sustainability objectives of modern architecture.

Main Questions 1: Considering the operational energy usage, which cladding system is more sustainable for buildings: aluminum or polycarbonate?

Answer:

Based on the operational energy usage data provided and the analysis of environmental impacts of aluminum and polycarbonate cladding systems during the operational phase, we can determine which cladding system offers more sustainability for buildings from an energy consumption perspective.

Energy Consumption Analysis:

Cooling Energy: The polycarbonate system uses significantly more energy for cooling than the aluminum system. This higher energy usage could be attributed to the higher transmissivity of polycarbonate, which, while allowing more natural light, can also increase heat gain, thereby requiring more energy to maintain thermal comfort.

Heating Energy: The heating energy required for the polycarbonate system is also substantially higher than that for the aluminum system. This could be due to the poor

insulative properties of polycarbonate compared to aluminum, necessitating more energy to heat the interior during cooler conditions.
Lighting Energy: I aluminum consumes more energy for lighting compared to polycarbonate. This can be attributed to aluminum's lower light transmittance, requiring more artificial lighting to maintain adequate light levels inside the building.
Consequently, Considering the total energy consumption across all categories—cooling, heating, and lighting—the aluminum cladding system emerges as the more sustainable option for buildings strictly in terms of operational energy usage. It is substantially more energy-efficient, consuming just about 20.1% of the energy used by the polycarbonate system. Although aluminum requires more energy for lighting, its significantly lower energy requirements for cooling and heating more than compensate for this increase.
Therefore, if operational energy efficiency is the primary criterion, aluminum cladding is more sustainable than polycarbonate when evaluating their impact on the sustainability of building operations. However, this analysis does not consider other factors like the impact on occupant comfort, the quality of the indoor environment, and the total lifecycle impact of the materials, which could also influence the overall sustainability assessment. For a complete evaluation, these factors should also be considered, potentially in combination with energy findings, to determine a cladding system's full environmental impact.

SUBQ 2-1: How does the hybrid system perform in terms of energy consumption for cooling, heating, and lighting compared to single-material systems?

Answer:

The hybrid cladding systems offer a compromise between the extremes of aluminum and polycarbonate, providing better overall energy efficiency than polycarbonate, particularly in reducing heating and cooling demands. For instance, in terms of cooling energy, Model 9 consumes only 15.81% of the energy used by polycarbonate. In heating, it uses 23.51% of the energy that polycarbonate does, and although its lighting energy consumption is 130.36% of that of polycarbonate, overall, Model 9 uses only 23% of the total energy consumed by polycarbonate, demonstrating superior performance compared to the single polycarbonate system.

Comparatively, the behavior of aluminum is more energy-efficient than that of Model 9. Aluminum's cooling energy use constitutes only 19.94% of the energy used by Model 9. For heating, aluminum consumes 82.19% of the energy used by Model 9, and for lighting, it uses 226.83% of the energy, which is approximately 2.2 times more than Model 9. However, the total energy consumption of aluminum amounts to 85.57% of that of Model 9, indicating that aluminum still maintains an edge in overall energy efficiency.

In summary, while both hybrid Model 9 and aluminum offer improvements over polycarbonate in specific areas, aluminum cladding remains the more energy-efficient option overall when compared to Model 9. Nonetheless, Model 9 significantly reduces energy usage compared to polycarbonate, striking a balance in energy consumption across cooling, heating, and lighting demands.

SUB Q2-2: How do the hybrid cladding systems contribute to meeting LEED certification standards compared to standalone aluminum and polycarbonate systems?

Answer:

The evaluation of cladding systems in terms of their ability to meet LEED certification standards reveals distinct performance characteristics for aluminum, polycarbonate, and hybrid systems. Although the aluminum cladding system demonstrates superior behavior in terms of energy usage, it falls short in meeting LEED certification requirements due to its inadequate spatial daylight autonomy (sDA) and annual sunlight exposure (ASE) performance. Both sDA and ASE are critical for achieving LEED credits related to daylighting and views, which aluminum cannot provide.

Similarly, the polycarbonate system, while allowing higher natural light penetration due to its material properties, significantly exceeds the LEED limit for ASE, leading to potential issues with glare and excessive solar heat gain, which could increase cooling demands. Moreover, its high total energy consumption detracts from its viability in terms of energy efficiency under LEED standards.

In contrast, hybrid cladding systems, which integrate features of both aluminum and polycarbonate, present a balanced solution. These systems are designed to harness the benefits of polycarbonate's light transmittance while mitigating its drawbacks through the thermal properties of aluminum. This synergy allows hybrid systems to achieve an sDA that complies with LEED standards while keeping ASE within acceptable limits. Additionally, while the total energy consumption of hybrid systems is approximately 14.4% higher than that of aluminum, it is significantly lower compared to polycarbonate. This modest increase in energy consumption over aluminum can often be offset by strategic energy strategies such as the integration of energy-efficient fixtures and renewable energy sources.

Therefore, hybrid cladding systems emerge as a more favorable option for achieving LEED certification. They not only address the shortcomings of single-material systems in terms of daylighting and energy performance but also offer a platform for further reductions in environmental impact through the adoption of advanced energy management strategies. This makes them a compelling choice for projects aiming to fulfill rigorous sustainability standards while balancing the trade-offs between energy efficiency, indoor environmental quality, and architectural aesthetics.

Main Question 2-2: how does a combined cladding system model influence the environmental Impact of Buildings and sustainability?

Answer:

the influence of a combined cladding system model on the environmental impact of buildings and their sustainability can be comprehensively assessed by examining key aspects of energy consumption, daylighting, and overall resource efficiency. A combined, or hybrid, cladding system integrates the strengths of different materials—such as aluminum and polycarbonate—in a single solution to optimize performance across several dimensions.

Energy Efficiency: Hybrid cladding systems are designed to capitalize on the thermal properties of materials like aluminum, which is highly effective in reducing heating demands due to its low thermal transmittance. Meanwhile, they incorporate elements

like polycarbonate to enhance cooling efficiency by managing solar gain more effectively than aluminum alone could. This strategic combination can result in a significant reduction in the total energy consumption for heating and cooling compared to systems using a single material. For instance, while Model 9's total energy usage is slightly higher than that of aluminum, it drastically cuts down on the consumption levels seen with polycarbonate systems, providing a more balanced energy usage profile.

Daylighting and ASE: One of the critical factors for achieving sustainability in building design is optimizing natural light, which not only reduces the need for artificial lighting but also enhances the well-being of occupants. Hybrid systems can be tailored to optimize spatial daylight autonomy (sDA) while controlling annual sunlight exposure (ASE) to prevent excessive heat gain and glare, which are common issues with high-transmittance materials like polycarbonate. By moderating these factors, hybrid cladding systems meet and can exceed LEED certification requirements for daylighting, contributing positively to a building's environmental profile.

Overall, a combined cladding system model significantly influences the environmental impact of buildings by enhancing energy efficiency, improving indoor environmental quality through better daylighting, and utilizing materials in a way that supports sustainability objectives. This holistic approach not only meets but often exceeds traditional sustainability metrics, providing a viable pathway to achieving higher sustainability standards in the construction industry. Such systems offer a practical solution to the complex challenge of balancing energy performance with environmental impact, making them an essential component of modern sustainable architectural practices.

General Question 2: How do various cladding systems impact the environmental performance of buildings and their compliance with the design principles of positive buildings during the operational phase?

Answer:

The environmental performance of buildings and their compliance with the design principles of positive buildings during the operational phase are significantly influenced by the choice of cladding systems. Various cladding systems offer distinct characteristics that affect a building's energy efficiency, resource use, daylight management, and overall sustainability footprint.

Energy Consumption: The selection of a cladding system is crucial in influencing a building's energy consumption during its operational phase. Understanding the inherent properties of cladding materials and the climatic conditions of a building's location enables the optimal utilization of these characteristics to reduce energy usage. Efficient cladding systems can significantly decrease the need for artificial heating and cooling, aligning with energy-efficient design principles and reducing the building's overall energy footprint. The selection of a cladding system directly influences the long-term environmental footprint of buildings through building's energy consumption during its operational phase.

By understanding the properties of cladding materials and the climatic potential of a building's location, architects can harness these characteristics to minimize energy

usage. Effective energy management through appropriate cladding can significantly reduce the environmental consequences associated with excessive energy consumption, such as greenhouse gas emissions and resource depletion, thereby enhancing the building's sustainability over its lifespan.

Daylighting and ASE Management: Optimizing natural light through effective daylighting strategies through employ the claddings systems characteristics not only improves occupant comfort but also decreases the need for artificial lighting, thus reducing energy consumption and its associated environmental impacts. Properly designed cladding systems that balance spatial daylight autonomy (sDA) and annual sunlight exposure (ASE) help in achieving this balance. Managing ASE effectively minimizes the risk of overheating and excessive cooling needs, further contributing to a lower environmental impact throughout the building's operational phase.

Sustainable Materials in Cladding Systems: The use of sustainable materials in cladding systems is pivotal to minimizing the environmental impact during the operational phase (B6) of buildings. This research specifically focuses on materials that have documented Environmental Product Declarations (EPD), ensuring that their production, use, and end-of-life impacts are comprehensively assessed and managed. For instance, the aluminum used in the modeled cladding systems is sourced from recycled materials, which significantly reduces the demand for virgin resources and lowers the embodied energy typically associated with aluminum production. Using recycled aluminum not only supports the circular economy but also enhances the overall sustainability of the cladding systems by mitigating the environmental impacts associated with material extraction and processing. Additionally, the incorporation of EPD-certified materials ensures that each component's environmental footprint is transparent and minimized, aligning with the broader objectives of sustainable building practices.

5.5 Research Findings and Conclusion

This research aimed to investigate passive design solutions focusing on geometry and materials, assessing their environmental impact for large office buildings. Utilizing energy usage calculations during the B6 stage, the study provided a comparative analysis of different geometries. The initial findings indicated that spherical geometry exhibited superior environmental performance, thus prompting further investigations into this shape. To address one of the main research questions, a sensitivity analysis was conducted on the effects of varying dimensions on the outputs of each geometry—specifically, thermal load and overall environmental impact. This analysis was crucial in determining which orientations would minimize environmental consequences, thereby identifying optimal directions for expanding geometric designs. For the sphere, radius directions emerged as a critical factor. Subsequent investigations focused on material usage, where two cladding systems, aluminum, and polycarbonate, were evaluated. Neither system alone could meet LEED standards, leading to the hypothesis that a hybrid system might prove more effective.

In the subsequent phase of the study, optimization was undertaken with a model designed to enhance daylight utilization while also achieving three principal sustainability objectives: minimizing thermal load, ensuring that Spatial Daylight Autonomy (sDA) exceeds 50%, and maintaining Annual Sun Exposure (ASE) below 10%.

The results highlighted the strategic placement of skylights across various facades as an effective approach to meeting these goals.

These conclusions not only highlight the efficacy of the selected geometric and material configurations in reducing environmental impact but also validate the hybrid cladding approach as a viable solution to meet rigorous sustainability standards. The research contributes to the broader discourse on sustainable architecture, providing a foundational framework for future studies on passive design strategies in urban office environments.

5.5.1 Suggestion and Solution: Architectural Principles of Spatial Structures to Address Positive Buildings (Case study: large Office in Boston)

This research, through modeling, analysis, and optimization of the proposed models, has successfully validated the hypotheses. The results demonstrate effective strategies for designing large office buildings. Based on these findings, several architectural principles can be recommended to design large office spaces in Boston to achieve positive building standards

5.5.1.1 Using the Regenerative Design Paradigm Method:

- **Parametric Structures**: This research employs the regenerative design paradigm as a foundational methodology for building design, specifically utilizing parametric structures (spatial structures).
- **Using Sustainable Materials for Cladding Systems:** The study focuses on sustainable materials for cladding systems, ensuring that each is certified by Environmental Product Declarations (EPD). This certification guarantees that the environmental impact of each component is carefully assessed and minimized, aligning with the principles of sustainable architecture.

5.5.1.2 Selecting Optimal Geometry for Climate-Responsive Building Design

This research has determined that for large office buildings in Boston, spherical geometries demonstrate superior performance in terms of energy usage during the use stage. The spherical form, due to its minimal surface area relative to volume, effectively reduces heat gain and loss. This geometric efficiency not only optimizes thermal regulation but also significantly lowers energy consumption for heating and cooling, aligning with sustainability objectives for urban office environments. Spatial structures, known for their ability to cover extensive openings without any supporting columns, further enhance environmental friendliness. These structures facilitate flexible, open interior layouts, ideal for large offices, and allow for the incorporation of innovative, curved forms that can adapt to specific site conditions and aesthetic requirements. Such findings underscore the potential of integrating specific geometric forms and spatial structures to enhance building performance in climate-specific contexts, providing both functional and environmental benefits.

5.5.1.3 Employing Hybrid Systems: Integrating Efficiency and Sustainability in Architecture

Integrating Efficiency and Sustainability in Architecture emphasizes the strategic use of combined materials to optimize building performance. By leveraging the unique

characteristics of both aluminum and polycarbonate, it becomes feasible to control energy consumption effectively and meet LEED certification standards. The optimization analysis conducted in this research illustrates how blending these materials in precise proportions can substantially enhance sustainability. For instance, the findings indicate the optimal balance of aluminum and polycarbonate needed to design a spherical large office building in Boston that adheres to LEED standards. Table 5-10 provides detailed guidance on the specific percentages of polycarbonate and aluminum required to achieve this balance, ensuring that each material contributes its strengths—whether it's thermal insulation, light transmittance, or durability—toward the overall environmental performance of the structure.

Table 5-10: Aluminum Ration and Polycarbonate Ratio in each geographic direction, Appendix D, Page469

Model Type	AL Ratio	PL Ratio
Model 5	93.17702	6.822985
Model 9	93.18423	6.815767

Table 5.11 presents the percentage of lighting openings allocated to each direction for a base model with a surface area of 1,519 square meters. These percentages are designed to be scalable, allowing the application of results to both larger and smaller models while maintaining compliance with LEED standards for Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE). This parametric approach ensures that the strategic distribution of lighting openings can be effectively adjusted according to different building sizes, thereby optimizing natural lighting and energy efficiency across diverse architectural scales. Consequently, the model's adaptability underscores its utility in varied design contexts, promoting sustainable architectural practices that meet stringent environmental and energy usage criteria.

Table 5-32: Area percentage of skylights by geographical direction, Appendix D, Page 470

Model Type	North(m2)	East(m^2)	Sout (m^2)	West (m^2)
Moddel5	0	13.58458	7.718461	10.95507
Model 9	0	11.1605	7.718461	13.33806

5.5.1.4 Local and Recycled Materials in Spatial Structure's cladding system to address Positive Buildings

Employing local and recycled materials in the construction of spatial structures is a crucial strategy for enhancing sustainability in positive building projects. The primary advantage of using local materials is the substantial reduction in transportation-related carbon emissions, which significantly lowers the overall carbon footprint of the project. Recycling materials that would otherwise contribute to landfill waste reduces the demand for virgin materials that require intensive extraction and processing, conserving natural resources and minimizing ecological impact. Incorporating materials certified by Environmental Product Declarations (EPD) adds transparency about the lifecycle environmental impacts, ensuring environmentally accountable production processes. This practice is not only a measure of sustainability but also poses an architectural challenge, encouraging architects to creatively integrate these materials into their designs. This integration enhances aesthetic qualities and achieves environmental objectives, exemplifying how sustainability can seamlessly merge with

contemporary architecture in structures designed to positively impact both the environment and building occupants. Prioritizing the use of local and recycled materials thus significantly enhances the sustainability of spatial structures and exemplifies environmental stewardship, leading the construction industry toward more sustainable building practices globally.

5.5.1.5 Advanced Intelligent Façade Systems in Spatial Structures

Employing advanced façade systems within spatial structures to support the architectural principles of positive buildings. These systems, designed with intelligent windows, leverage the flexibility of spatial structures to integrate multi-functional elements such as adaptive shading and daylight management systems. By employing technologies that adjust to environmental conditions, these façades can significantly reduce operational energy demands while maintaining comfort and compliance with LEED standards. The potential of spatial structures is effectively utilized to design façades that are not only energy-efficient but also versatile in accommodating various façade elements, enhancing the building's overall sustainability and functionality.

5.5.1.6 Integrated Design Approach

Encourage collaborative processes among all stakeholders from the earliest stages of design to ensure all aspects of sustainability are considered, including energy efficiency, material selection, and occupant comfort. In particular, the potential of spatial structures should be fully leveraged to enhance sustainability and structural efficiency. This requires a multidisciplinary approach where civil engineers, architects, environmental scientists, and other experts work together to design spatial structures that not only meet aesthetic and functional requirements but also optimize environmental performance. By integrating expert knowledge in the design process, spatial structures can be crafted to utilize fewer resources, reduce energy consumption, and provide enhanced comfort, thereby supporting the overarching goals of sustainable development in the built environment.

5.5.1.7 Developing Calculation Methods for Energy Efficiency and Environmental Impact of Geometric Designs

One of the significant contributions of this research is the development of formulas designed to calculate thermal loads and environmental impacts for different architectural geometries. These formulas represent a considerable advancement in the field of sustainable building design, providing professionals with a systematic approach to quantitatively assess the performance impacts of their design choices. By utilizing machine learning methods, complex and time-consuming simulation processes can be streamlined significantly, facilitating the initial stages of design. This enables designers to estimate the environmental impacts of their projects quickly and more accurately without the need for time-consuming manual simulations. This innovation not only encourages the integration of scientific methods into creative processes but also ensures that sustainability is embedded as a fundamental component of architectural innovation. It is essential to note that these formulas achieve the greatest accuracy

under consistent project conditions, making them reliable tools in standardized settings.

5.6 Innovation

This section underscores the novel contributions of this thesis to the field of architectural design, particularly within the context of regenerative and positive building practices. The innovations presented not only advance the academic discourse but also propose practical solutions with the potential for significant impact on sustainable development.

5.6.1 Development of Hybrid Cladding Systems

A core innovation of this research is the development and analysis of hybrid cladding systems that intelligently combine different materials to optimize environmental performance. This approach leverages the benefits of aluminum and polycarbonate to enhance energy efficiency and daylight autonomy while reducing the thermal load. The successful implementation of these systems illustrates a breakthrough in cladding technology, providing a model that can be tailored to different building types and climatic conditions.

5.6.2 Integration of Parametric Design with Environmental Simulation

This thesis introduces an innovative integration of parametric design tools with environmental simulation software, enhancing the precision and adaptability of architectural designs to their environmental contexts. This method allows for real-time simulations that adjust building parameters based on environmental data, a significant advancement in architectural design practices that promotes more sustainable and responsive building strategies.

5.6.3 Pioneering Regenerative Design Frameworks

The research contributes a pioneering framework for regenerative design, which involves not just minimizing negative impacts but actively enhancing the environment. This framework has been applied to large office buildings in urban settings, demonstrating how architectural designs can contribute to urban sustainability by enhancing ecosystem services and reducing buildings' carbon footprints

5.6.4 Practical Implementation and Scalability

Another significant innovation is the development of practical and scalable regenerative design practices that can be implemented in current and future architectural projects. These practices are designed to be adaptable to various scales, from individual buildings to urban developments, providing a blueprint for integrating sustainability deeply into architectural practice

5.6.5 Advanced Analytical Methods and Interdisciplinary Approaches

This research has pioneered the development of advanced analytical methods and interdisciplinary approaches that significantly enhance the ability of architects and researchers to assess and optimize the environmental impact of building designs. By integrating machine learning techniques with traditional architectural analysis, this thesis introduces a sophisticated methodological framework that not only investigates

the impact of dimensions on building performance but also applies a multifaceted approach to sustainability. These innovative tools leverage diverse knowledge domains, blending advanced computational methods with environmental science to create a holistic understanding of sustainable practices. Designed for user-friendliness and seamless integration into existing design processes, these methods facilitate a broader adoption of sustainable practices within the architectural community. This approach not only enriches the analytical capabilities but also encourages a deeper engagement with complex sustainability issues, promoting a more comprehensive and nuanced application of sustainable architecture principles.

5.7 Critical Review of Architectural Strategies to Address Positive Buildings

5.7.1 Overview

In this thesis, the researcher explores the architectural principles of spatial structures aimed at achieving "positive buildings"—the new paradigm's goal to not merely reduce environmental harm but actively foster ecological restoration. As we advance this concept, it is crucial to critically assess the practical challenges and ambiguities associated with implementing such structures. The investigation centers on the optimal selection of geometry and materials for cladding systems during the operational phase. The researcher deliberately limited the analysis to this phase to maintain a focused and manageable scope, acknowledging that while a comprehensive life cycle assessment could offer broader insights, such considerations are beyond the intent of this study. This section aims to critically evaluate the intervening factors that challenge the realization of truly positive buildings, providing a structured discourse on the optimistic yet arduous pursuit of environmentally proactive architecture.

This thesis rigorously evaluates the feasibility of realizing positive buildings and delineates the substantial challenges that could obstruct these ambitious goals. It scrutinizes specific interventions during the operational phase to determine their efficacy in overcoming these challenges and contributing to the overarching goal of achieving buildings with a net positive environmental impact.

5.7.2 Defining 'Positive' in Building Performance

The term 'positive' often brings to mind energy generation, typically suggesting that buildings should produce more energy than they consume. However, this thesis argues for a broader interpretation. A truly positive building should not only be a net producer of energy but also actively reduce environmental pollutants. The researcher explores this expanded definition through two key interventions—geometry and materials—selected for their potential during the operational phase of a building's lifecycle. This phase is identified as the most impactful in terms of potential pollutant production due to energy consumption. The ambiguity in current definitions suggests a need for a more nuanced understanding that encompasses multiple dimensions of environmental impact.

5.7.3 Evaluation of Methodological Approaches

In this thesis, a critical focus was placed on evaluating the operational phase's impact on pollutant production associated with energy consumption. The employed methodology utilized an indirect approach to quantify the pollutant outputs resulting from specified energy consumption levels. This approach highlights the significant interplay between building design and environmental impact, emphasizing how architectural decisions directly influence energy efficiency and subsequent pollutant emissions.

To facilitate this analysis, the study extensively utilized parametric modeling tools such as Rhino and Grasshopper, along with climate analysis plugins like Honeybee and Ladybug. These tools were instrumental in assessing how different architectural geometries and cladding materials influence a building's energy requirements. Additionally, OpenLCA software was employed to calculate the environmental impact of the energy used, providing a more comprehensive view of the potential environmental costs associated with different energy scenarios. These combined tools enabled the simulation of energy consumption based on varied design configurations and environmental conditions, offering a basis for estimating the associated pollutant production indirectly.

However, this approach presents inherent limitations. While parametric models and OpenLCA provide robust frameworks for simulation, the primary challenge lies in the accuracy of these simulations in predicting real-world dynamics within buildings. Theoretical models can approximate the impacts of design changes on energy consumption and environmental impact but may not fully capture the complexities of real-life building operations or maintenance anomalies. Additionally, the reliance on generic data for energy consumption and pollutant production ratios introduces variability in the outcomes, depending on the source and type of energy being modeled.

Moreover, the indirect method of assessing pollutants based on energy consumption necessitates assumptions about energy sources and their pollution coefficients, which can vary significantly between regions and over time. This adds an additional layer of complexity to interpreting the results and applying them universally.

During the analysis, two intervention factors—geometry and cladding—were examined under the hypothesis that optimized designs could significantly reduce energy consumption and thus pollutant production. While these factors demonstrated potential in simulation environments, translating these findings into practical, actionable strategies in real-world settings remains challenging due to the aforementioned limitations.

This critical evaluation underscores the need for robust, adaptable modeling techniques that can integrate more dynamic, real-world data, reducing reliance on assumptions and enhancing the accuracy of predictions regarding energy consumption and pollutant production.

5.7.4 Practical Implications and Feasibility

5.7.4.1 Challenges in Implementing Geometric Innovations to Address Positive Buildings

In exploring the potential of architectural geometry to foster positive environmental impacts, this thesis acknowledges the multifaceted challenges encountered during the operational phase of buildings. The implementation of innovative geometric designs, while pivotal for advancing ecological restoration, introduces complex intervening factors that can significantly impede the realization of net positive environmental outcomes. This overview delineates the scope of such challenges, setting the foundation for a deeper investigation into the specific technical, economic, and systemic barriers. Through this analysis, the researcher aims to unravel the complexities involved in operationalizing geometric innovations, highlighting how these can complicate the pursuit of buildings that not only consume less but actively contribute to environmental sustainability

5.7.4.1.1 Constructability:

The complexity of geometric designs significantly impacts their constructability. Innovative forms, designed to optimize energy efficiency and minimize environmental impact, frequently necessitate advanced construction techniques that may not be widely available or economically viable. Additionally, indirect factors such as the labor force and the production processes of geometry itself can introduce significant challenges. These complexities require a concerted, interdisciplinary collaboration to manage and mitigate the potential for increased environmental pollutants during construction. Thus, achieving such ambitious designs demands not only technical skills and advanced methodologies but also a coordinated approach among various construction disciplines to ensure both feasibility and environmental integrity.

5.7.4.1.2 Economic Implications:

The economic implications of complex geometric designs in buildings are a crucial aspect to consider. These designs, although potentially superior in terms of energy efficiency and environmental benefits, typically incur higher initial costs than conventional structures. While energy-positive buildings can generate excess energy, thus offering potential economic returns over time, the overarching goal of achieving substantial environmental benefits goes beyond mere energy production. It is essential to evaluate if the environmental gains translate into tangible economic benefits that can serve as a viable incentive for project stakeholders. Establishing clear, supportive policies and incentives is necessary to make these environmentally progressive designs economically attractive and feasible for wider adoption.

5.7.4.1.3 Integration of Advanced Building Technologies:

The effectiveness of geometric designs in achieving positive impacts is greatly enhanced by integrating advanced building technologies. However, the adaptation of

these technologies into geometrically complex structures poses significant challenges due to technical limitations and the need for specialized skills.

5.7.4.1.4 Energy Consumption and Environmental Impact:

Geometric design is pivotal in determining the energy performance of buildings. Well-conceived designs can significantly reduce energy consumption through strategies such as enhanced natural ventilation, optimized solar gain, and minimized thermal bridging. Additionally, the integration of modern systems like Building Integrated Photovoltaics (BIPV) and the exploitation of climatic potential and passive solutions can effectively turn buildings into net energy producers, achieving positive energy status. However, achieving a design that also delivers a positive environmental impact extends beyond energy metrics. The process of creating such geometric forms itself consumes energy, which in turn can have a significant environmental footprint as detailed in this thesis. This complexity underscores that while positive energy outcomes are achievable, the broader goal of positive environmental impact involves intricate challenges. The necessity for regenerative design principles becomes apparent, as they not only compensate for the energy used in construction but also enhance the building's overall environmental contribution. This holistic approach requires a nuanced understanding and application of both passive and active design strategies to truly align architectural practices with environmental sustainability goals.

5.7.4.1.5 Material Use in Constructing Geometry:

The choice of materials for constructing architectural geometries is a critical factor that significantly influences the environmental impacts of buildings. While certain materials can facilitate energy generation—thus aiding in achieving positive energy buildings—their production, transportation, and installation processes can entail substantial environmental costs. From extraction to onsite delivery, every step in the material lifecycle can contribute to environmental degradation. Furthermore, the waste generated during demolition also poses serious environmental challenges. Although using recycled materials can reduce the impact by limiting the demand for virgin resources and minimizing waste, the recycling processes themselves often generate pollutants. Therefore, a holistic approach to material selection is essential. This approach should not only consider the energy performance of materials but also their entire environmental footprint, including production, lifecycle longevity, and end-of-life recyclability. By carefully selecting materials that balance these aspects, it is possible to move closer to truly positive environmental impacts, though the challenges are substantial and require innovative solutions and systemic changes in material processing and construction practices.

5.7.4.1.6 Labor and Systemic Factors:

The labor force and construction systems prevalent in a region play critical roles in determining the feasibility of executing advanced geometric designs. Complex designs typically require a highly skilled workforce and specialized equipment, which may not be universally available. This scarcity of skilled labor and appropriate technology can

severely limit the practical application of innovative geometries intended to enhance building sustainability. Moreover, the lack of expertise and advanced construction technologies can lead to inefficiencies and increased resource use during the construction phase, potentially negating some of the positive environmental impacts these designs aim to achieve.

5.7.4.2 Challenges in Implementing Cladding Systems for Positive Buildings

This section examines the specific challenges that cladding systems encounter during the operational phase of buildings, with a focus on achieving positive environmental impacts. Cladding systems play a pivotal role in the energy performance and sustainability of buildings. However, during the operational lifecycle, numerous challenges emerge that can impede the realization of truly positive buildings. These challenges include durability and maintenance demands, the environmental impact of material production and disposal, and the integration of these systems with energy-efficient technologies. By exploring these operational obstacles, we aim to uncover the complexities involved in deploying cladding systems that not only meet aesthetic and functional requirements but also contribute significantly to the building's overall environmental goals.

5.7.4.2.1 Material Selection:

The selection of materials for cladding systems is pivotal in defining a building's environmental and energy performance during the operational phase. Optimal materials should not only enhance thermal insulation and energy efficiency but also contribute actively to the building's overall sustainability goals. To truly support the concept of positive buildings, these materials must go beyond conventional criteria to include properties that facilitate renewable energy generation and reduce environmental pollutants. However, the challenge lies in sourcing materials that embody these advanced functionalities while adhering to sustainable building practices, presenting multiple challenges:

Sustainability of Materials: Traditional cladding materials often fall short of current sustainability benchmarks, primarily due to energy-intensive and polluting production processes. For a building to align with positive impact goals, materials must be sourced that are produced using environmentally friendly methods that minimize energy consumption and pollution.

Durability and Maintenance: While materials that enhance sustainability and energy efficiency are crucial, they often come with higher initial costs and may require more sophisticated maintenance routines. These factors can significantly affect their long-term viability and overall cost-effectiveness, challenging their adoption despite their beneficial properties in terms of energy conservation and environmental impact.

Availability and Cost: The market availability of high-performance, sustainable cladding materials is not uniform globally, and their high cost can be a significant barrier. This restricts their widespread adoption and poses a challenge to achieving buildings that are both energy-positive and environmentally sustainable. The limited accessibility of these materials hinders the progress toward universally applicable solutions for positive building practices.

5.7.4.2.2 Technological Integration Challenges

Integrating advanced technologies such as photovoltaic cells and high-performance insulative materials into cladding systems is a critical factor in enhancing the energy performance of buildings, potentially leading to positive energy outputs. However, while these technologies can significantly reduce a building's energy demand and contribute to generating surplus energy, they also introduce substantial challenges that can impede achieving broader positive environmental impacts:

- **Production and Installation Impacts:** The manufacturing and installation processes for advanced cladding technologies often involve significant environmental costs. The production of high-tech materials such as photovoltaics and specialized insulators typically requires intensive resource consumption and results in considerable emissions. These factors can negate some of the environmental benefits these technologies are intended to provide.
- **Complexity of Design and Installation:** Implementing these technologies within cladding systems demands precise design and highly skilled installation. This complexity not only increases the potential for errors during construction but also escalates the overall project costs and timelines. Such complexities may lead to additional resource use and waste, further complicating the environmental footprint of the project.
- **System Compatibility:** Ensuring that these new technologies harmonize with existing building systems and architectural designs is another significant challenge. Structural compatibility, aesthetic integration, and the efficient interconnection with the building's energy systems are essential for maximizing the benefits of advanced cladding technologies. However, achieving this integration often requires additional modifications to existing structures, which can be resource-intensive and environmentally impactful.

5.7.4.2.3 Regulatory and Standards Compliance During the Operational Phase:

Navigating the regulatory landscape for building materials and construction techniques presents substantial challenges during the operational phase of buildings, particularly in achieving positive environmental impacts through cladding systems:

- **Building Codes and Standards:** Compliance with local building codes and sustainability standards critically shapes the operational performance of cladding systems. These regulations are generally designed to ensure safety, efficiency, and to minimize environmental harm. However, they typically do not yet fully embrace the concept of positive environmental impacts—most standards focus on reducing negatives rather than promoting positives. This lack of comprehensive definitions and benchmarks for truly positive impacts can restrict the adoption of innovative materials and technologies that might excel beyond mere compliance, complicating efforts to achieve environmental benefits that are genuinely transformative.

- **Certification Processes:** Obtaining certifications such as LEED, BREEAM, or other sustainability credentials is often a time-consuming and costly process, with these systems primarily geared towards mitigating negative impacts rather than fostering positive ones. The processes involved not only delay the adoption of innovative solutions but also impose significant costs, which can deter investment in technologies that contribute to a building's net positive impact. Moreover, the stringent requirements to maintain these certifications can limit operational flexibility, hindering the adaptation of building systems to newer, more effective environmental solutions as they emerge.
- **Use of Recycled or Recyclable Materials:** While the use of recycled or recyclable materials can contribute toward achieving a net positive environmental impact by reducing the demand for virgin resources and minimizing waste, the production processes of these materials themselves often lead to significant pollutant outputs, as evidenced by the Environmental Product Declarations (EPDs) referenced in this thesis. This paradox highlights the complexity of achieving true sustainability, where the benefits of using less harmful materials might be offset by the environmental costs of their production.

These regulatory and compliance challenges affect the ongoing effectiveness of buildings in achieving positive environmental impacts. Achieving recognition for positive contributions requires a shift in regulatory frameworks and certification standards towards models that value and incentivize environmental restoration and enhancement, not just the reduction of harm. This shift is crucial for advancing the construction industry towards practices that truly support sustainable development.

5.7.4.2.4 Environmental Impact Assessment of Cladding Systems:

Overview of Lifecycle and Environmental Impact Assessing the full environmental impact of cladding systems requires a holistic view that encompasses the entire lifecycle of the materials used—from production and installation to maintenance and end-of-life disposal. This comprehensive approach is essential to truly understand and mitigate the environmental burdens associated with these systems. Challenges and Dual Nature of Technological Advances The technological advancements in cladding systems present significant dual challenges:

While these systems offer the potential for substantial energy savings and positive energy generation, the environmental costs incurred during their production, installation, and integration phases necessitate careful consideration.

The production of advanced, environmentally active materials often involves processes that, although aimed at reducing the operational carbon footprint, can themselves be significant sources of pollutants. This paradox highlights the need for ongoing advancements in material science and production techniques to ensure that the materials used are as environmentally benign as possible.

The Need for a Comprehensive Approach Implementing cladding systems that contribute to buildings with net positive impacts requires tackling these multifaceted

challenges through a comprehensive approach that spans material selection, technological integration, regulatory compliance, and rigorous environmental impact assessment. Successfully overcoming these challenges is crucial for advancing the design and construction of buildings that not only meet but exceed current sustainability standards. This strategic approach ensures that the benefits of innovative cladding materials are maximized, while their environmental liabilities are effectively managed and mitigated, supporting the progression towards more sustainable building practices.

5.7.5 Scope and Limitations in Addressing Positive Buildings

This section outlines the specific limitations and the defined scope of the study, shedding light on the generalizability of the results and the particular constraints encountered:

Defined Scope: The research specifically targets the operational phase of buildings, concentrating on how architectural geometry and cladding systems can contribute to achieving positive environmental impacts. By focusing on this phase, the study provides detailed insights into specific interventions but does not cover other lifecycle stages of buildings such as construction and end-of-life phases, which also hold significant environmental implications.

Resource Constraints: The scope of empirical data collection was limited by resource availability, relying heavily on simulations and theoretical modeling. While these methods provide valuable predictions and insights, they may not fully capture the complex dynamics of real-world scenarios, which could affect the study's applicability to practical settings.

Technological and Geographic Specificity: The technological tools used in this research, such as advanced simulation software, might not be accessible in all regions or contexts, potentially limiting the wider applicability of the study's recommendations. Moreover, the study's findings are influenced by the specific geographic and climatic conditions assumed in the simulations, which may not be representative of all potential application areas.

Regulatory and Standards Compliance: The variability in regulatory environments across different regions can significantly impact the feasibility of implementing the study's recommendations universally. The research does not encompass all possible regulatory conditions, which could limit the practical application of its conclusions outside the studied context.

Impact of Limitations on Generalizability: These limitations highlight the need for careful consideration when applying the study's findings beyond the original research context. They suggest that while the research provides important insights into achieving positive buildings, these insights should be adapted to specific local conditions to ensure their relevance and effectiveness.

Including a discussion on the scope and limitations is crucial for situating the study within its appropriate academic and practical contexts. It helps in setting realistic expectations for the applicability of the research findings and in guiding future work to expand on the initial study's boundaries.

5.7.6 Reflecting on Positive Building Paradigms Based on the Results

the critically evaluates The findings from this investigation highlight the complexities involved in achieving buildings that are both energy-positive and have a net positive environmental impact.

5.7.6.1 Critique of Positive Building Paradigms:

The paradigms explored in this thesis, including LEED-certified projects and other sustainability benchmarks, often emphasize energy efficiency and the minimization of negative impacts. While these are commendable goals, the results indicate that truly positive impacts—where buildings provide clear environmental benefits beyond their operational footprints—require a more integrated approach combining both passive and active solutions.

5.7.6.2 Scalability and Real-World Applicability:

The scalability of positive building strategies presents a significant challenge. Although the integration of active solutions such as photovoltaic systems and advanced HVAC technologies can lead to buildings that produce more energy than they consume, the environmental costs associated with manufacturing, installing, and maintaining these systems can detract from their positive contributions. The production of high-tech materials and systems often involves significant emissions and resource consumption, which might negate the benefits achieved through operational energy savings.

Moreover, while passive design elements like natural lighting, enhanced insulation, and thermally efficient materials show potential for reducing energy needs, their effectiveness varies greatly with geographic and climatic conditions. This variability challenges the universal applicability of certain design principles and underscores the need for tailored solutions that consider local environmental conditions and resource availability.

5.7.6.3 Integration Challenges:

Achieving a balance between active and passive solutions is critical for maximizing positive impacts. Active systems can indeed propel a building to net-positive energy status; however, without a holistic consideration of their environmental production costs, the broader goal of net-positive environmental impact remains elusive. This points to a gap in current building standards and certifications, which may not adequately account for the lifecycle impacts of active solutions used to achieve positive energy outcomes.

Reflecting on the paradigms of positive buildings explored in this thesis, it becomes clear that while significant strides have been made towards more sustainable construction, achieving genuinely positive impacts requires a deeper integration of both design philosophy and technology application. Future frameworks for positive buildings should incorporate comprehensive lifecycle assessments that go beyond operational performance to include the environmental costs of material production and system installation. By doing so, the construction industry can better align with the

ultimate goal of sustainable development, which is not merely to reduce harm but to actively improve environmental conditions.

5.8 Recommendations for Future Research Initiatives

This research has focused on the utilization phase of spatial structures, with the objective of aligning them with the principles of positive building design. However, to genuinely advance toward edifices that yield a net positive environmental impact, it is imperative for future research to adopt a more ambitious scope. Such expansion should encompass the exploration of regenerative and restorative design principles. These principles should aim not merely to mitigate environmental impacts but to proactively enhance ecological health and promote systemic restoration. By setting such high-performance goals, the research can contribute significantly to the evolution of sustainable architecture into truly regenerative practices.

5.8.1 Integrating Regenerative Design Principles

Future research should integrate regenerative design principles that go beyond minimizing negative impacts to actively enhancing the environment. This involves using materials and systems that contribute to the ecosystem, such as bio-based materials and systems that regenerate natural resources. Studies could explore the lifecycle benefits of such materials, from production through end-of-life, assessing their overall contribution to environmental restoration.

5.8.2 Application of Intelligent Geometry and AI

The application of intelligent geometry, enhanced through artificial intelligence, offers significant potential for optimizing building performance and environmental impact. AI can be used to develop complex geometric designs that adapt to changing environmental conditions, maximizing natural light while minimizing heat loss. Research should focus on quantifying the benefits of these intelligent systems in reducing the operational energy requirements and actively contributing to environmental sustainability.

5.8.3 Development of Regenerative Materials

Investigating the development and application of regenerative materials that can heal themselves or absorb carbon from the atmosphere could revolutionize the construction industry. These materials could significantly reduce the environmental footprint of buildings during their operational phase and beyond. Future studies should evaluate the practicality and effectiveness of incorporating such materials into spatial structures, considering both technological feasibility and economic viability.

5.8.4 Integrative Approaches with Photovoltaics and Pollution Mitigation Systems

Recent advancements in sustainable building technologies emphasize the critical role of integrated systems that simultaneously manage energy production and environmental purification. The strategic deployment of Building Integrated Photovoltaics (BIPV) alongside advanced energy storage solutions is instrumental in developing buildings that not only supply excess energy but also stabilize the energy grid. Importantly, incorporating photovoltaic systems with pollutant-detoxifying capabilities presents a dual-function strategy that enhances the building's operational efficiency while actively reducing environmental pollutants. Such systems are pivotal for pushing the boundaries of traditional energy positivity to include tangible environmental benefits. Rigorous scientific research and comprehensive analysis are imperative to refine these systems' design and functionality, ensuring they surpass existing sustainability metrics. By doing so, these integrated solutions can substantially increase energy output while significantly diminishing the buildings' ecological impact, thereby redefining standards in environmentally responsible architectural practices.

Final Remarks, While this research has laid the groundwork by focusing on use stage of spatial structures, there is a significant opportunity to expand into regenerative and intelligent architectural solutions. Future work should aim to create buildings that not only meet sustainability standards but actively contribute to ecological and environmental health. This shift towards regenerative architecture will require innovative approaches to design, materials, and construction techniques, all aimed at achieving a truly sustainable future.

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Appendix A
Research experience With TREND (Boston)

A.1 Abstract

The abstract for the chapter titled "Research Experience in Boston" encapsulates the author's academic journey as a member of the "Trend" program at Northeastern University. During this tenure, the author engaged in a structured curriculum, taking one course per semester. The initial semester was dedicated to studying "Life Cycle Assessment of Buildings and Materials," followed by "Sustainable Design and Construction" in the subsequent semester. This chapter delves into how this educational experience was instrumental in advancing the author's thesis, providing a practical and theoretical foundation that enriched the research.

The narrative is structured around three core themes: Interaction and Communication, Scientific Approach, and Exceptional Academic Infrastructure. Each category is explored in detail to demonstrate how they collectively contributed to the author's research acumen and overall thesis development.

- Interaction and Communication: This section discusses the dynamic academic environment and the collaborative engagements that fostered a deeper understanding of regenerative design principles and their practical applications.

- Scientific Approach: Here, the focus is on the methodological and analytical skills honed through coursework and research activities, emphasizing the integration of sustainable practices in architectural design.

- Exceptional Academic Infrastructure: The chapter highlights the state-of-the-art facilities and resources at Northeastern University, which provided a conducive setting for innovative research and exploration in sustainable architecture.

This chapter serves as a documentary of the enriching experiences garnered during the author's time in Boston, underscoring their significance in the completion of the thesis on architectural principles for regenerative design of spatial structures.

A.2 Interaction and communication

A.2.1 Dynamic Interdisciplinary Learning in the Trend Program:

My activities during the year-long engagement at the Department of Civil and Environmental Engineering at Northeastern University in Boston were multifaceted

and enriching. Interactions and Communications involved engaging with a diverse academic community, participating in collaborative projects, and networking with professionals and peers. These interactions enhanced my communication skills and broadened my understanding of global perspectives on sustainable architecture. The opportunity to interact with international students from diverse countries and academic fields presented a valuable experience in enhancing interaction, communication, and knowledge exchange. The convergence of students with varied research backgrounds as active members of the Trend program facilitated a dynamic environment for interdisciplinary learning. This interaction proved to be highly beneficial, as it enabled an awareness of the methodologies currently employed across different fields concerning the topic of sustainability. The diversity of perspectives and approaches brought to the table by these students enriched the discourse on sustainable practices, making it an intellectually stimulating and attractive aspect of the experience.



Figure A. 2: Collaborative International Research Meeting with Trend Members

Given the interdisciplinary nature of my thesis, it is imperative to engage in dialogue and exchange insights with fellow researchers to stay abreast of the latest scientific advancements pertinent to my area of study. Membership in the "Trend" research group afforded me an exceptional opportunity to facilitate effective cross-disciplinary communication. This collaborative environment was instrumental in enhancing my understanding and integration of engineering principles into my modeling work. The ability to interact with experts from diverse scientific backgrounds within this group not only enriched my research perspective but also solidified the foundational engineering concepts essential to my thesis.



Figure A. 5: Collaborative International Research Meeting with Trend Members

A.2.2 Synergistic Academic and Professional Exchanges in Sustainable Architecture:

Engaging in collaborative research with fellow trend members presented a valuable opportunity to explore sustainability from an interdisciplinary perspective. During the first semester, an article entitled "The possible influence of positive buildings in the real estate market in the framework of urban transition" provided an excellent basis for examining the concept of positive buildings, offering a novel viewpoint by integrating economic factors. In the subsequent semester, the discourse with trend members on circular economy issues within smart cities facilitated the generation of an innovative research title, making the process notably engaging.



Figure A. 8: Collaborative research.

A.2.3 Integrating with NSUBO: My Journey in Sustainable Building Advocacy:

Joining the NSUBO community and actively participating in its weekly meetings has been an enriching experience. Established in 2016 by a group of students from Northeastern University's Sustainable Building Systems master's program, NSUBO welcomes both graduate and undergraduate students from all disciplines. The organization is dedicated to fostering a community passionate about the evolution of

the built environment, offering insights into the latest advancements in building science, technology, and design.
The mission and vision of NSUBO are succinctly encapsulated in their statements: "We drive sustainable and regenerative design, construction, and operation of the built environment. Our vision is to cultivate a thriving, diverse community committed to creating a built environment that achieves net positive systems in terms of water and energy, financial and social equity, and ecological and human health."
This academic articulation emphasizes the inclusive nature of the NSUBO community, its foundational goals, and the ambitious vision it holds for the future of the built environment.



Figure A. 11: Weekly meeting by NSUBO

NSUBO's Professional Affiliations: NSUBO are affiliated with the Built Environment Plus, formerly known as the Massachusetts Chapter of the USGBC (US Green Building Council). They have become the 'lead advocate' for the WELL Building Standard as well as host the Living Building Challenge Collaborative of Boston. NSUBO Group are also Northeastern University's ASHRAE (formally American Society of Heating, Refrigeration & Air-Conditioning Engineers) Student Branch. The ASHRAE Boston Chapter was started in 1912 and provides opportunities for students to interact with local industry professionals. Their focus on building systems, energy efficiency, indoor air quality, refrigeration and sustainability within the industry incorporates the HVAC&R industry to the multi-disciplinary approach that NUSBO stands for.



Figure A. 14: NSUBO's Professional Affiliations, Northeastern University webpage

NSUBO are also an academic member of NESEA – the Northeast Sustainable Energy Association – a group that works to advance the adoption of sustainable energy

practices in the built environment by cultivating a community where practitioners share, collaborate, and learn. NESEA's commitment to increasing sustainability in the built environment aligns with NUSBO's mission and helps facilitate our engagement with professionals in the sustainability community.

Participating in the professional meetings organized by NSUBO, which featured presentations from companies specializing in the design of sustainable buildings, was an invaluable experience. These sessions not only provided insights into current industry practices but also facilitated a platform for knowledge exchange and networking. Through these interactions, I gained an understanding of innovative design strategies and sustainable practices employed in the field, enhancing both my theoretical knowledge and practical skills. The meetings served as a conduit for integrating theoretical concepts with real-world applications, thereby enriching my professional growth and contributing to my repertoire of sustainable design methodologies.



Figure A. 17: Presenting sustainable design systems by professional companies

A.3 Academic and Technical Proficiency: Coursework, Tools, and Applications

A.3.1 First Semester: Life cycle Assessment of Materials and Buildings

During the first semester, I had the privilege of enrolling in a course titled' Life cycle assessment of materials and buildings within the Civil & Environmental Engineering Department, supervised by Professor Matthew Eckelman. My selection of this course was strategically aligned with the methodology of my research, rendering it particularly pertinent to my thesis topic. The class composition was diverse, encompassing students from various research backgrounds, including civil engineering, material science, and environmental building disciplines. This diversity facilitated a comprehensive learning experience, providing me with the opportunity to delve into different aspects of life cycle assessments and broaden my understanding of interdisciplinary approaches in sustainability studies.

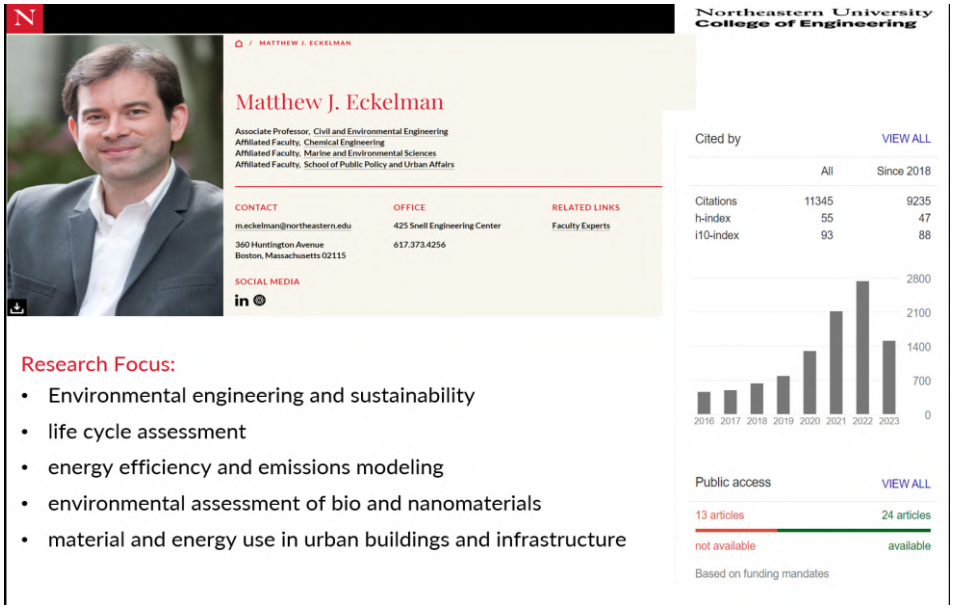


Figure A. 20: Professor Eckelman Background research

Below is a refined summary of my accomplished tasks, highlighting the collaborative aspect of the final project:

- Developed proficiency in various software tools, including OpenLCA and One Click LCA, for assessing the environmental impacts of buildings and materials, demonstrating an integration of theoretical and practical methodologies.
- Completed thirteen detailed assignments centered on life cycle assessment, enhancing my analytical skills and deepening my understanding of sustainable practices.
- Collaborated on a comprehensive team project to model Timber wood, where I contributed to the analysis of the results and the development of strategic recommendations to mitigate the environmental impacts associated with material use, showcasing a blend of teamwork, research, and practical problem-solving capabilities.

A.3.1.1 Final project : Life Cycle Assessment of TimberHP Wood Fiber Insulations: TimberBoard and TimberFill

The visit to a factory specializing in the production of hardwood panels for interior walls and cladding presented an outstanding opportunity to gain insights into the manufacturing processes of eco-friendly products. This experience allowed for a deeper understanding of the challenges faced in the development of more sustainable products. Our strong partnership with the manufacturer, established for a client-commissioned project, underscored the importance of comprehending the life cycle assessment process in the context of executing projects. This interaction not only facilitated a practical learning experience but also highlighted the critical role of industry collaborations in advancing sustainability within product manufacturing.



Figure A. 23: The Timber wood Factory (Reference: Author)



Figure A. 26: Some materials using in timber wood production process, (Reference: Author)

In the subsequent sections, the project process, analysis, and final results are elucidated in detail, providing a comprehensive overview of the methodologies employed and the outcomes achieved. This detailed exposition not only delineates the procedural steps taken but also offers an in-depth examination of the analytical frameworks and the consequent findings, thereby presenting a holistic understanding of the project's scope and impact:

A.3.1.2 Goal and Scope

A.3.1.2.1 Goal

TimberHP by GO Lab (TimberHP) is an innovative building technology company whose main goal is to evaluate the environmental impacts of wood fiber insulation by TimberHP. TimberHP is in the process of launching three wood fiber insulating products, loose-fill insulation, insulation batt, and rigid board insultation. Wood fiber insulation provides several advantages over traditional insulation products, most notably its carbon sequestering abilities, recyclability, and absence of harmful toxins. TimberHP hopes to gain an understanding of the environmental impacts associated with their wood fiber insulation products. The following case study was created to provide insight into the environmental impacts, namely global warming potential and energy consumption these products will have based on projections developed before

manufacturing. Once operational data for the facility is available, the results of this study may be adapted to better reflect environmental impact and develop an official Environmental Product Declaration (EPD) for these products.

This study has been commissioned by TimberHP. This study will be carried out by a group of Northeastern graduate students: Alexandre Gulka, Rachel Henry, Zinat Javanmard, Hema Vaishnavi Panguluri, Sai Revanth Paruchuri, and Jiayue Xing as part of the course CIVE 5275 Life Cycle Assessment of Materials, Products, and Infrastructure. Interested parties for this study include investors and internal stakeholders at TimberHP. The intended users of this study will be TimberHP, with the understanding that information from this study may be adapted and used to develop EPDs for their wood insulation products in the future.

A.3.1.2.2 Scope

- **Product system:**

TimberHP offers a range of wood fiber insulation products: TimberBoard, TimberBatt, and TimberFill. This study will explore the environmental impacts of TimberBoard and TimberFill using manufacturing projections developed prior to the start of manufacturing.

TimberBoard combines softwood fibers, PMDI adhesive, and paraffin wax to create rigid boards which can serve as exterior continuous insulation or interior insulation for walls, ceilings, and floors. TimberBoard offers stable R-values ranging from 3.4 to 3.75 per inch and comes in thicknesses ranging from 1 to 9.26 inches. TimberBoard can be used in place of traditional foam board insulation such as expanded polystyrene (EPS), extruded polystyrene (XPS), and polyisocyanurate (PIR).

TimberFill combines softwood fibers and borate to create loose-fill insulation that can be densely packed into stud wall, joist, and rafter cavities or loose fill blankets for attics. TimberFill offers stable a stable R-value of 3.8 per inch. TimberFill can be used in place of spray foam (PU), fiberglass, and cellulose insulation.

- **Functional Unit:**

The primary function of both products is to provide resistance to thermal transfer to lower building energy demands. The functional unit (FU) for this study was defined as 1 m^2 of installed insulation material with a thickness that gives an average thermal resistance equal to an R_{SI} value of 1 $m^2 \cdot K/W$. TimberBoard provides an average R value of 3.575 $h \cdot ft^2 \cdot °F/Btu \cdot in$ and TimberFill has an R value of 3.8 $h \cdot ft^2 \cdot °F/Btu \cdot in$. The required thickness of TimberBoard and TimberFill was calculated as 0.0404 meters and 0.038 meters respectively, shown below.

$$R_{SI}\text{ -1 } [m^2 \cdot K/W] = R_{IP}\text{ - 5.68 } [h \cdot ft^2 \cdot °F/Btu]$$

$$\frac{5.68\ \mathrm{h \cdot ft^2 \cdot °F/Btu \cdot in}}{3.575\ \mathrm{h \cdot ft^2 \cdot °F/Btu \cdot in}} \times 0.0254\ \frac{\mathrm{meters}}{\mathrm{inch}} = 0.0404\ \mathrm{meters}$$

$$\frac{5.68\ \mathrm{h \cdot ft^2 \cdot °F/Btu \cdot in}}{3.8\ \mathrm{h \cdot ft^2 \cdot °F/Btu \cdot in}} \times 0.0254\ \frac{\mathrm{meters}}{\mathrm{inch}} = 0.0380\ \mathrm{meters}$$

The reference flow (RF) defines the amount of product required to satisfy the primary function as defined by the functional unit. The target density for TimberBoard is $140\ \frac{\mathrm{kg}}{\mathrm{m^3}}$ the reference flow for TimberBoard was calculated as 5.65 kg, shown below. TimberFill

can be densely packed into wall cavities, achieving an estimated density of $3\,\frac{\text{lb}}{\text{ft}^3}$, or blown into attic spaces, achieving an estimated density of approximately $1.5\,\frac{\text{lb}}{\text{ft}^3}$. For the purposes of this study, we modeled TimberFill assuming it will be used for dense pack with a density of $3\,\frac{\text{lb}}{\text{ft}^3} = \frac{48.06\ \text{kg}}{\text{m}^3}$. The reference flow for TimberFill was calculated as 1.83 kg shown below.

$$0.0404\ \text{m} \times 1\ \text{m}^2 \times 140\ \frac{\text{kg}}{\text{m}^3} = 5.65\ \text{kg/FU}$$

$$0.038\ \text{m} \times 1\ \text{m}^2 \times 48.06\ \frac{\text{kg}}{\text{m}^3} = 1.83\ \text{kg/FU}$$

- **System Boundaries:**

EN 15804+A2 Section 5.2 specifies that EPDs should include cradle-to-gate (A1-A3), end-of-life (C4), and reuse, recycling, and recovery potential (D) as listed in **Error! R eference source not found.**. For the purposes of this study, a cradle-to-gate (A1-A3) assessment was performed. Impacts associated with installation (A4-A5), use (B1-B7), and end of life (C1-C4, D) stages were not considered in this study.

Table A. 1: Description of the system boundary

Production			Installation		Use Stage							End-of-Life				Next Product System
Raw material supply (extraction, processing, recycled material)	Transportation to manufacturer	Manufacturing	Transportation to building site	Installation into building	Use / application	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction / demolition	Transportation to EoL	Waste processing for reuse, recovery, or recycling	Disposal	Reuse, recovery, or recycling potential
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
X	X	X	MND	MND	MND	MND	MND	MND	MND	MND	MND	MND	MND	MND	MND	MND

X=declared module, MND=module not declared

- **Manufacturing Process:**

As shown in Figure A.10, TimberFill (red), TimberBatt (yellow), and TimberBoard (green) are produced in three production lines. TimberFill and TimberBatt are produced using Refiner #1; TimberBoard is redirected to Refiner #2 at the stage of pre-steaming bins to #3 production line. High efficiency clone is used to separate wood chips with moisture contents.

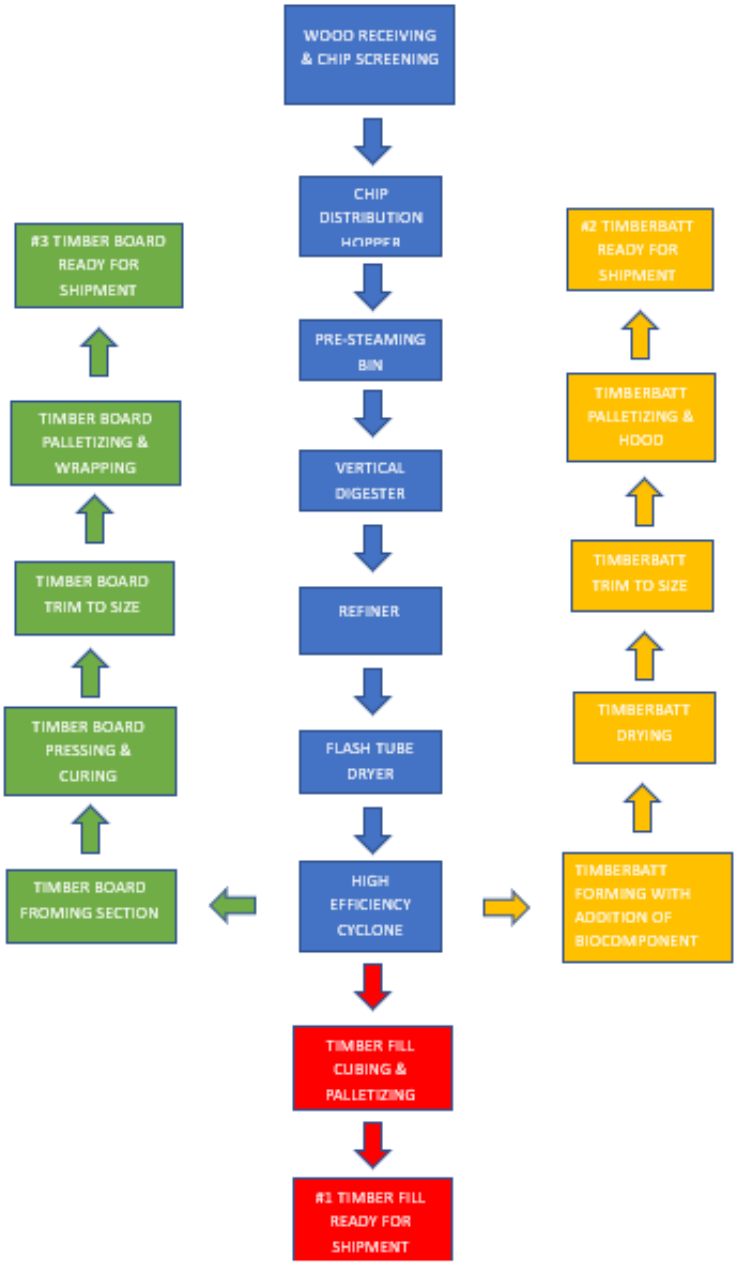


Figure A. 29: Manufacturing process for three production lines

- **Temporal Coverage:**

This study uses projected manufacturing data of the TimberHP facility that was calculated prior to the start of manufacturing. If this study is to be adapted for the creation of an EPD after manufacturing has begun, operational data shall cover a production period of one year and the period of data must be clearly documented as outlined in EN 15804+A2 Section 6.3.7. Generic, publicly available, data used must be measured within the last ten years.

- **Spatial Coverage:**

This study focuses on manufacturing in North America and Europe. When available, regional specific data was used. If regional specific data was not available, the global average was used.

- **Allocation Procedure**

Following the hierarchy established in ISO 14044:2008, when necessary, mass-based allocation was used to calculate inventory values.

- **Impact assessment Methods**

In accordance with EN15804+A2 Section 6.6 TRACI 2.1 and Cumulative Energy Demand were selected as impact assessment methods. The impact categories covered in these impact assessment methods that are required for EN15804+A2 are shown in Tables A.2 and A.3 below.

Table A. 2: TRACI 2.1 Impact Categories

Impact Category	Unit
Acidification	Kg SO2 eq
Eutrophication	Kg N eq
Fossil Fuel Depletion	MJ surplus
Global Warming	kg CO_2 eq
Ozone Depletion	Kg CFC-11 eq
Smog	Kg O3 eq

Table A. 3: Cumulative Energy Demand Impact

Impact Category	Unit
Nonrenewable, fossil	MJ
Renewable, water	MJ

- **Data and Data Quality**

The data used in this case study was primarily projected manufacturing data provided by TimberHP. Models were created using openLCA software version 1.11.0 along with the ecoinvent 3.6 database.

A.3.1.3 Literature Review

Wood is a renewable resource. Construction products based out of wood for buildings are produced with considerably less energy and associated carbon emissions. Wood-based building materials are hygroscopic, meaning that they can hold and release water molecules (Sathre & O'Connor, 2010). Due to their hygroscopic nature, wood and other bio-based building materials can act as moisture-buffering materials (Osanyintola & Simonson, 2006). Wood fiber insulation can serve other purposes after its use phase such as incineration which can help to avoid burdens associated with heat production or it can be turned into other bio-based products and avoid being disposed of completely into landfills. The carbon absorbed during the tree's life remains locked and

sequestrated in the insulation product until disposed of and released (Bros-Williamson, 2022). Stored carbon could potentially stay in wooden building products for a life cycle over 100 years. Therefore, biogenic carbon would be considered during A5 if incinerated at end of life; otherwise, the biogenic carbon should be added in module A1 according to environmental performance indicators (EPD International n.d.).

- **Wood Fiber Properties**:

The physical properties of wood fibers are important as they provide consistency for various uses of production. Wood is a ligneous plant that can be used to create numerous products, including by-products of chemical pulping processes, such as fiber, chips, sawdust, or fine shavings (Korjenic et al., 2016). Since wood fibers alone are difficult to use to create insulation products, binders are frequently added to help in the compression process. In the past, synthetic insulating materials have been made with polymers made of volatile organic chemicals (VOCs) that are hazardous to human health and the environment and are sometimes challenging to recycle and reuse. The use of bio-based composites as binders with performance comparable to petrochemical-based products has been the subject of extensive investigation. There are several examples of combining naturally occurring binders with natural fibers, such as wood fibers that use lignin, tannins, proteins, and oils (Lacoste et al., 2018).

- **Environmental Impacts:**

In a case study on retrofitting buildings, (Bianco et al., 2017) compared wood fiber insulation to extruded polystyrene insulation (XPS). The study demonstrated that wood fiber insulation has strong thermal inertia capabilities. When tested on roofing surface areas, wood fiber insulation helped manage indoor air temperature fluctuations. Additionally, it notes that the embodied energy of wood fiber insulation products is roughly 4,942 MJ/m^3, as opposed to 3,236 MJ/m^3 for XPS insulation and 3,045 MJ/m^3 for polyurethane insulation. Despite wood fiber insulation requiring more energy for production, the study did not consider the sequestrated carbon in the material which shows its negative global warming potential (GWP), compared with equivalent synthetic materials with a positive GWP.

A life cycle assessment (LCA) of "cradle to grave" performed by Schulte et al. in 2021 compared STEICOZELL blown-in wood fiber insulation, THERMO stopwolle Hanf hemp fiber insulation, Flaschfloc blown-in flax insulation and miscanthus using eight specimens as certified miscanthus products was not available. A comparison of the total environmental impacts of the bio-based insulation materials were first presented and then they were compared to the non-renewable insulations, EPS and stone wool. The life cycle impact assessment (LCIA) was conducted using the indicator approach ReCiPe. Per function unit (FU), wood fiber was found to be the least impactful to the environment. The functional unit was defined as 1 m2 of external wall of a residential building with 0.24 W m−2 K−1 for 70 years, fulfilling legal fire resistance and health and safety standards. The global warming of wood fiber was 2.75 kg CO_2 eq. as compared to 11.7 kg CO_2 eq, 13.62 kg CO_2 eq, 2.95 kg CO_2 eq for hemp fiber, flax and miscanthus, respectively.

In terms of the usability of wood fiber, installation was regarded as easier and healthier to use. For example, the characteristics of wood fiber insulation are minimal toxic gases

released, fewer synthetic petrochemical smells and more pleasant to the touch when handling compared with other synthetic insulation types according to (Sutton A, 2011).

- **Health and Wellbeing:**

Products made of wood fiber are beneficial to health because they aid to interior settings. According to research by (Korjenic et al., 2016), wood fibers and other natural fibers have a good impact on healthy living by trapping tiny dust particles. Lowering the noise level and shielding the building from weather damage. Given that wood fiber is vapor open, it permits moisture to move through building materials without vapor barriers. As a temperature and moisture buffer, it tends to control indoor climate conditions, helping to keep buildings warm in the winter and cool in the summer. These advantages help preserve healthy indoor air quality, which improves occupant thermal comfort and lowers allergens and other respiratory health problems.

The author (Liddell H, 2008) found that Wood fiber insulation doesn't release volatile organic compounds (VOCs) during production or after installation in the form of off gassing like synthetic insulation does. Over time, VOCs can be particularly harmful to inhabitants, producing mild irritation of the nose, eyes, and throat as well as nausea, headaches, and dizziness. Synthetic petrochemical compounds, however, have the potential to create more serious issues, such as allergy and non-allergic rhinitis, some types of lung cancer, liver or kidney damage, and damage to the central nervous system.

A.3.1.4 Life Cycle Inventory

The following sections detail the assumptions and reasoning used to calculate the life cycle inventory (LCI) for TimberBoard and TimberFill. A full LCI list can be found in Appendix 10.1 and 10.2.

A.3.1.4.1 Materials

A.3.1.4.1.1 Timber Board

TimberBoard is comprised of wood fiber from softwood chips, PMDI adhesive, and paraffin wax. Inventory data provided by TimberHP was given in terms of projected output per day. These values were converted to be in terms of the defined reference flow, 5.65 kg of TimberBoard, shown in Table A.4 below. The reference flow accounts for 3.74E-3% of the projected daily production.

Table A. 4: TimberBoard Materials

Materials	Dose by Weight	Mass [short ton/day]	Mass [kg/RF]
Wood Chips (dry)	93.5%	155.51	5.28
PMDI adhesive	5%	8.32	0.28
Paraffin Wax	1.5%	2.49	0.08
TimberBoard	-	166.32	5.65

- **Transportation:**

Transportation requirements were calculated in ton-kilometer, which equates to the mass of material multiplied by the distance traveled. TimberHP sources wood chips from multiply sawmills with an average distance of 57 miles from the Madison, Maine facility. PMDI adhesive is sourced from BASF in Wyandotte, Michigan. Paraffin wax is sourced from two manufacturers, Hexion Inc. in North Carolina and Walker Emulsions in Ontario, Canada. It was assumed that half of the paraffin wax came from each supplier. Table A.5 shows the amount of transportation required for each material.

Material	Mass [tonne/RF]	Distance [km]	[tkm]	Truck Loads [tonne]
Wood Chips (wet)	1.16E-2	91.73	1.068	33
PMDI adhesive	3.11E-4	1,451.62	0.4520	139
½ Paraffin Wax (NC supplier)	4.67E-5	1,544.97	0.0722	22
½ Paraffin Wax (ONT supplier)	4.67E-5	1039	0.0485	22

Table A. 5: TimberBoard Transportation

- **Packaging:**

TimberBoard is stacked on wooden pallets and wrapped with plastic hood wrap provided by Balcan. It was assumed that TimberBoard required 1.56 pallets per short ton and 2.27 lbs. of hood wrap per pallet. The mass of each material for the defined reference flow was calculated, shown in Table A.6 below.

Material			
Pallet	**[pallet/short ton]**	**[pallet/kg]**	**[pallet/RF]**
	1.56	1.72E-3	9.72E-3
Hood Wrap	**[lbs/pallet]**	**[kg/pallet]**	**[kg/RF]**
	2.27	1.03	0.01

Table A. 6: TimberBoard Packaging

A.3.1.4.1.2 TimberFill:

TimberFill is comprised of wood fiber from softwood chips and borate. Inventory data provided by TimberHP was given in terms of projected output per day. These values were converted to be in terms of the defined reference flow, 1.83 kg of TimberFill, shown in Table A.7 below. The reference flow accounts for 2.12E-3% of the projected daily production.

Materials	Dose by Weight	Mass [short ton/day]	Mass [kg/RF]
Wood Chips (dry)	93%	88.89	1.70
Borate	7%	6.65	0.13
TimberFill		95.04	1.83

Table A. 7: TimberFill Materials

- **Transportation:**

TimberHP sources borate from RoseMill in West Hartford, Connecticut. RoseMill sources the material from a mine in Turkey. Table A.8 below shows the amount of transportation required for each material.

Table A. 8: TimberFill Transportation

Material	Mass [tonne/RF]	Distance [km]	[tkm]	Truck Loads [tonne]
Wood Chips (wet)	3.75E-3	91.73	0.3442	33
Borate (CT-ME)	1.41E-4	495.68	0.21	20
Borate (TR-CT)	1.41E-4	10,197.09	4.31	

- **Packaging:**

TimberFill is bagged into 12in x 24in x 16 in bales using LDPE/LLDPE sheeting and stacked onto pallets. Pallets are then wrapped using Black Hawk 'Cynch Extreme Max Blown Machine Film'. It was assumed TimberFill requires 1.67 pallets per short ton. Each pallet requires 224 ft of 41 ¼ in. wide of bale wrap which comes in 12,000 ft rolls assumed to be 357 lbs./roll. Each pallet requires 144 ft of 20 in. wide pallet wrap which comes in 6,000 ft rolls. The approximate weight per roll of pallet wrap was unknown. The approximate weight per square foot of bale wrap was calculated and used for pallet wrap as well. The mass of each material for the defined reference flow was calculated, shown in Table A.9 below.

Table A. 9: TimberFill Packaging

Material					
Pallet	**[pallet/short ton]**	**[pallet/kg]**	**[pallet/RF]**		
	1.67	1.84E-3	3.37E-3		
Bale Wrap	**[lbs/ft]**	**[ft/pallet]**	**[lbs/pallet]**	**[kg/pallet]**	**[kg/RF]**
	2.98E-2	224	6.66	3.023	1.02E-2
Pallet Wrap	**[lbs/ft2]**	**[ft2/pallet]**	**[lbs/pallet]**	**[kg/pallet]**	**[kg/RF]**
	8.60E-2	240	2.064	6.96E-3	3.15E-3

A.3.1.4.2 Electricity

TimberHP's facility is powered entirely by a hydropower plant located adjacent to the property. Electricity is generated at high voltage, 4,160 kV, then stepped down to 115 kV. Lastly, transformers are used to convert from high voltage to medium voltage, 13.8 kV. This medium voltage electricity is used throughout the manufacturing process. TimberBoard requires 501 kWh per short ton which equates to 3.12 kWh per RF. TimberFill requires 483 kWh per short ton which equates to 0.974 kWh per RF. According to International Standard IEC 60038, high voltage is defined as anything about 35 kV and medium voltage is defined as voltages between 1 kV and 35 kV.

A.3.1.4.3 Natural Gas

Natural gas is used to power boilers to create steam used in the manufacturing process and to heat the facility. TimberBoard and TimberFill each require 1.8 mmBtu/short ton which equates to 1.12E4 Btu/RF of TimberBoard and 3.62E3 Btu/RF of TimberFill.

A.3.1.4.4 Water

Water usage was given in terms of daily use for the entire facility. The facility has three main water sources, filtered water, river water, and city water. Manufacturing uses primarily river water. For the purposes of this study, river water was the only input water flow considered. Mass based allocation was used to determine the river water demand for TimberBoard and TimberFill as well as their output river emissions and wastewater. The facility uses 997 gallons per minute of river water and outputs 123 gallons per minute of river emissions and 336 gallons per minute of wastewater. TimberHP produces 95.04 short tons of TimberFill, 118.8 short tons of TimberBatt, and 166.32 short tons of TimberBoard per day. TimberBoard production accounts for 43.75% of daily production and TimberFill accounts for 25% of daily production. Table 6.10 below shows the input and output water quantities for both products.

	TimberBoard		TimberFill	
Water Flow	**[gal/min]**	**[gal/RF]**	**[gal/min]**	**[gal/RF]**
River Input	436	23.5	180	3.14
River Output	280.72	15.14	159.5	2.79
Wastewater	146.96	7.92	84	1.46

Table A. 10: Water Usage

A.3.1.4.5 Biogenic Carbon

Biogenic carbon is known as the amount of carbon dioxide stored in wood or paper products that was removed from the atmosphere. This quantity of carbon dioxide can be modeled as a negative input value, given that this carbon dioxide will remain stored in the product rather than return to the atmosphere through degradation. The carbon content in tree species ranges from approximately 47%-52% (Nicodemus and Williams, 2004). Assuming a mixed variety of tree species are used for wood chip production, an assumed carbon content of 48% was used. The quantity of carbon in the specified reference flow for TimberBoard and TimberFill was found and converted to quantity of carbon dioxide using the ratio of molecular weights for carbon and carbon dioxide. This quantity of carbon includes the carbon stored in the softwood chips as well as in the wooden pallets used for shipping. The amount of biogenic carbon for both TimberBoard and TimberFill was calculated as 9.62 kg CO_2 and 3.10 kg CO_2 respectively. The impact assessment method used, TRACI 2.1, does not account for biogenic carbon sequestration. The net value of carbon dioxide emissions produced for both products was found by subtracting the amount of biogenic carbon in each product from the output value of carbon dioxide equivalent found from the model.

A.3.1.4.6 Outputs

Information regarding manufacturing outputs was not provided. Given the similarity between the processing of woodchips in TimberHP's manufacturing of insulation products and paper production, outputs from an already established paper production unit process in the ecoinvent database was used. From the ecoinvent database, "paper production, woodcontaining, lightweight coated | paper, woodcontaining, lightweight coated | Cutoff, U" outputs from European production of lightweighted paper was used. This unit process models 1kg of lightweighted paper. To be used in our model, the

outputs were scaled to the reference flow for both TimberBoard and TimberFill. The outputs used can be seen in Appendix 10.1 and 10.2.

A.3.1.5 Impact Assessment

The models created in openLCA for both TimberBoard and TimberFill were run using TRACI 2.1 and Cumulative Energy Demand impact assessment methods. The following section summarizes the results obtained.

A.3.1.5.1 TimberBoard

Table A.11 shows the total output value for each impact assessment category for TimberBoard. Before accounting for biogenic carbon, the total carbon dioxide equivalent value for global warming potential was 2.96 kg CO2 eq.

Table A. 11: TimberBoard Impact Assessment

Impact Category	Value
Global Warming Potential	-6.66 kg CO_2 eq
Ozone Depletion	4.34E-07 kg CFC-11 eq
Acidification Potential	1.08E-02 kg SO_2 eq
Eutrophication Potential	8.40E-03 kg N eq
Fossil Fuel Depletion	6.32 MJ Surplus
Energy Use, Non-Renewable	51.98 MJ
Energy Use, Renewable, Water	12.86 MJ

- **Global warming potential:**

Diagram A.1 illustrates the main contributors to global warming potential for TimberBoard in terms of percentage of the total. The amount of biogenic carbon, which describes carbon sequestered is 3.6 times greater than the amount of greenhouse gas emissions. Looking at the greenhouse gas emissions, 2.96 kg CO2 eq, PMDI adhesive production and natural gas are the top contributors. PMDI adhesive and natural gas make up 60.5% and 25.7% of greenhouse gas emissions and 14.2% and 6.2% of the net global warming potential respectively.

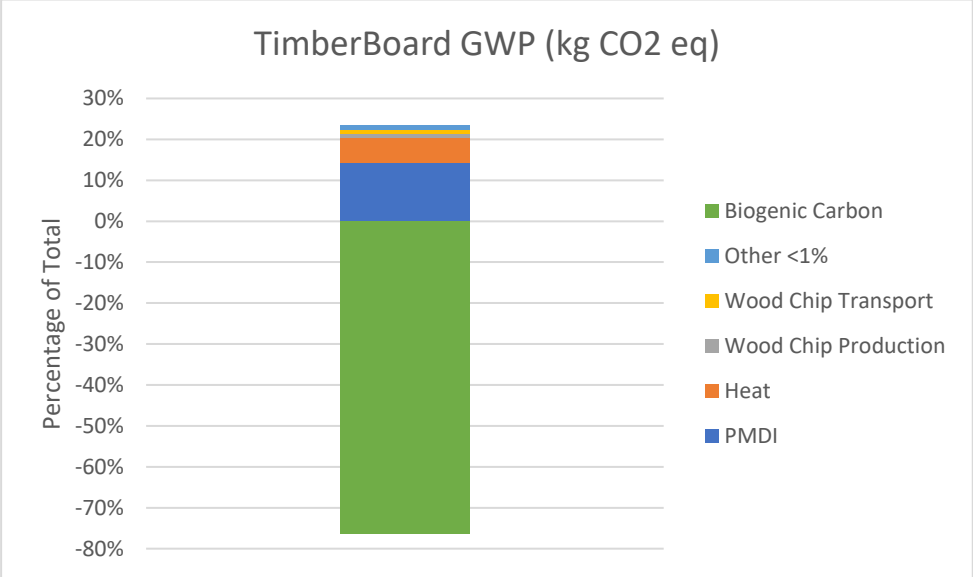


Diagram A. 2: TimberBoard Global Warming Potential

- **Environmental Impacts**

Diagram A.2 below illustrates the top contributors to environmental impacts for TimberBoard in terms of percentage of the total value. Across all environmental impact categories examined in this study, PMDI adhesive production was by far the largest contributor ranging from 49.2% for fossil fuel depletion to 82.7% for ozone depletion. Wood chip production was the second highest contributor to ozone depletion and acidification with 7.4% and 9.7% respectively. Wastewater was the second highest contributor to eutrophication with 10.8%. Heat production from natural gas was also a major contributor to fossil fuel depletion with 29.3%.

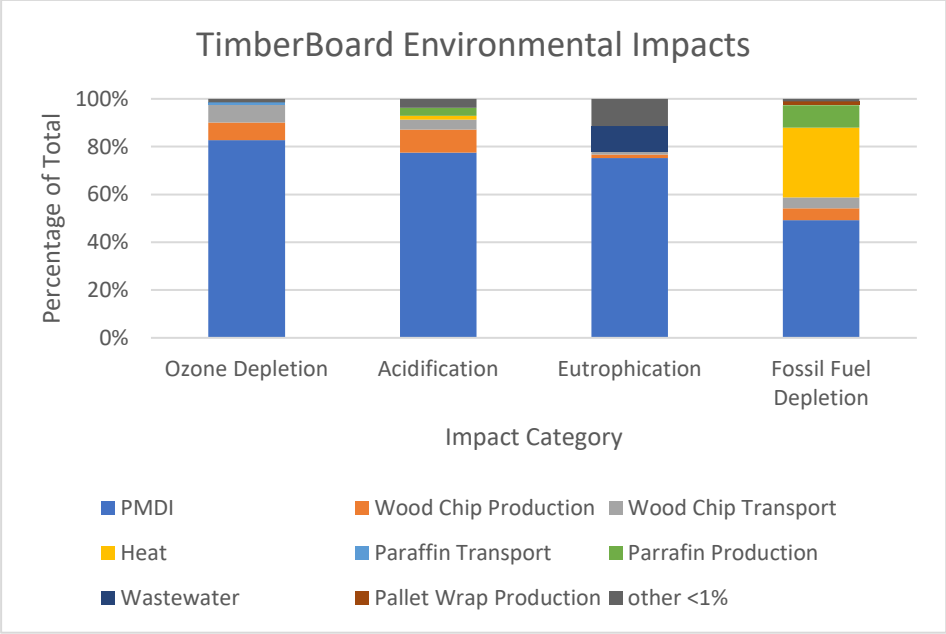


Diagram A. 5: TimberBoard Environmental Impacts

- **Energy Use**

Diaram A.3 illustrates the use of non-renewable fossil fuel energy for TimberBoard production in terms of percentage of the total value. Similarly, to environmental impacts, PMDI adhesive production and heat from natural gas are the top contributors to fossil fuel use with 55.4% and 23.8%. Given that fossil fuel use has been highly linked to negative environmental impacts, it makes sense that processes that use a large amount of fossil fuels will contribute the most to environmental impacts.

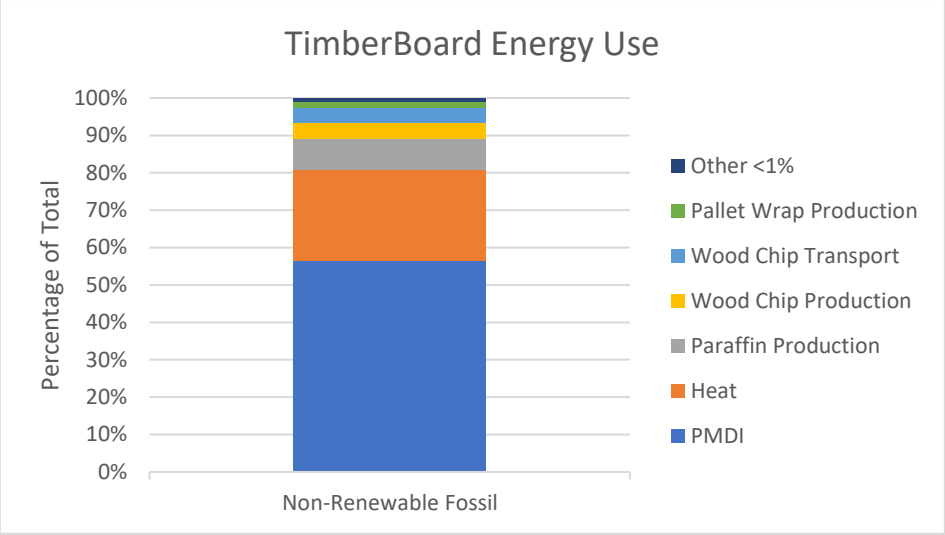


Diagram A. 8: TimberBoard Non-Renewable Energy Use

Diagram A.4 illustrates the use of renewable energy, specifically hydropower, for TimberBoard in terms of percentage of the total value. The transformation from high to medium electricity made up most of the energy use for hydropower with 91.7%. PMDI adhesive production and wood chip production also contributed to hydropower energy use with 5.0% and 1.8% respectively. The unit processes used for PMDI and wood chip production used the global averages, meaning some portion of global PMDI and wood chip production uses hydropower.

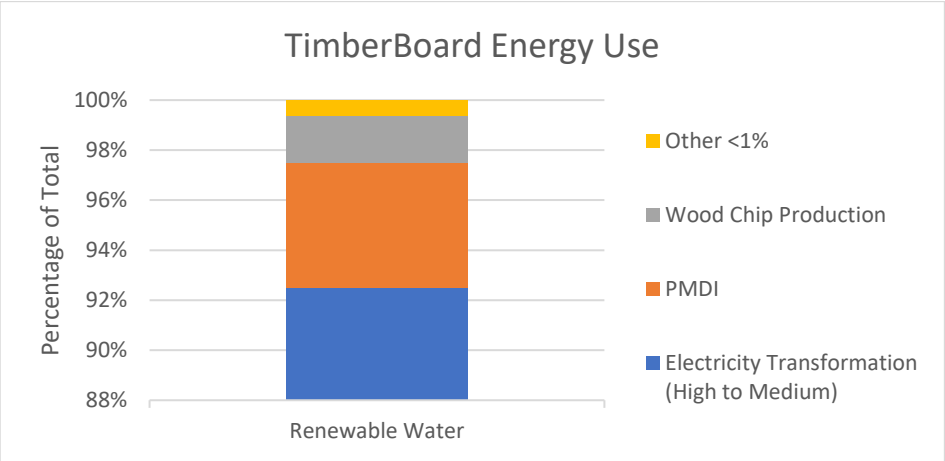


Diagram A. 11: TimberBoard Renewable Energy Use, Water

A.3.1.5.2 TimberBoard

Table A.12 shows the total output value for each impact assessment category for TimberFill. Before accounting for biogenic carbon, the total carbon dioxide equivalent value for global warming potential was 0.576 kg CO2 eq.

Impact Category	Value
Global Warming Potential	-2.60kg CO_2 eq
Ozone Depletion	2.50E-8 kg CFC-11 eq
Acidification Potential	1.10E-3 kg SO_2 eq
Eutrophication Potential	6.0E-4 kg N eq
Fossil Fuel Depletion	0.96 surplus
Energy Use, Non-Renewable	6.66 MJ
Energy Use, Renewable, Water	3.81 MJ

Table A. 12: TimberFill Impact Assessment

Summary

- **Global Warming Potential**

Diagram A.5 below illustrates the main contributors to global warming potential for TimberFill in terms of percentage of the total. Similar to the TimberBoard, the biogenic carbon is 5.1 times greater than the amount of greenhouse gas emissions. When taking a closer look at the graph, it is evident that heat and waste are the biggest contributors. Both heat and waste are the leading contributors to global warming potential and acidification respectfully.

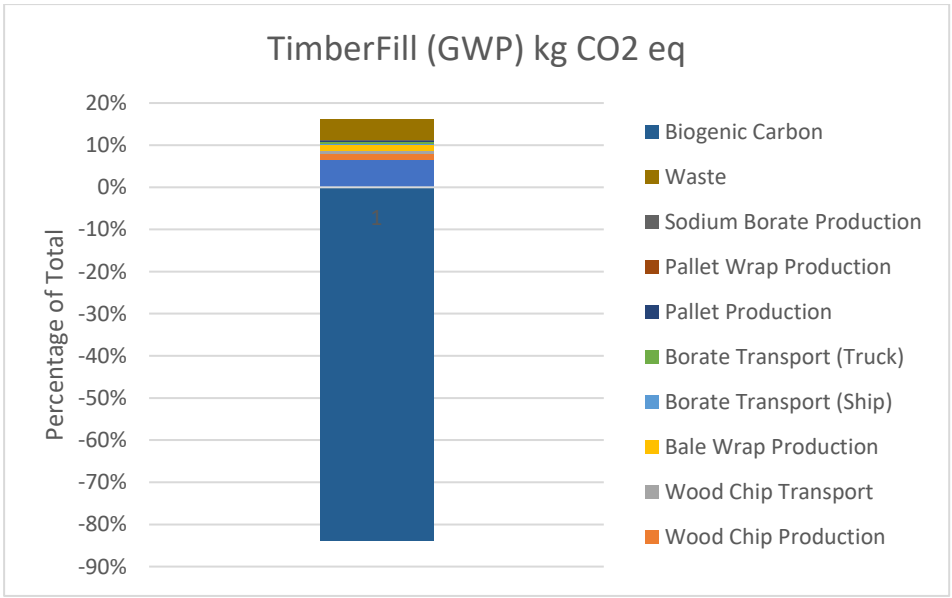


Diagram A. 14: TimberFill Global Warming Potential

- **Environmental Impacts**

Diagram A.6 illustrates the top contributors to environmental impacts for TimberFill in terms of percentage of the total value. Across the board (excluding acidification), electricity transformation was the highest contributor ranging from 65% for Ozone Depletion to 37% for fossil fuel depletion. On the other hand, the main contributor for

acidification is wood chip production with 56% contributing to that category. Heat was very apparent across the board with 45% contributing to fossil fuel depletion.

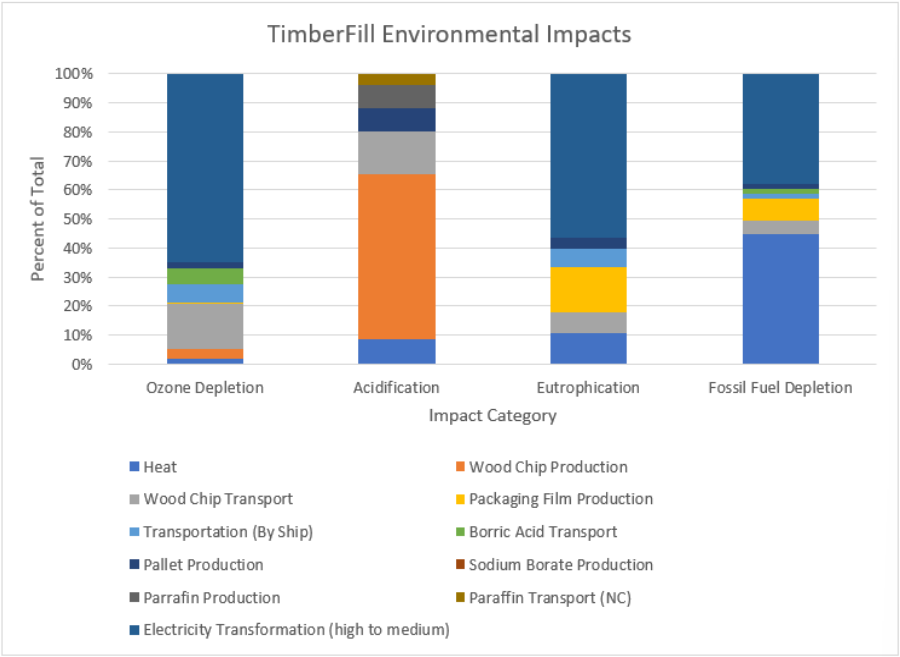


Diagram A. 17: TimberFill Environmental Impacts

- **Energy Use**

Diagram A.7 illustrates the use of non-renewable fossil fuel energy for TimberFill production in terms of percentage of the total value. Similar to the environmental impacts for TimberFill, the two main contributors are electricity transformation and heat at 38% and 43% respectively. It is logical that heat (combustion of fossil fuels) contributes the most to environmental impacts.

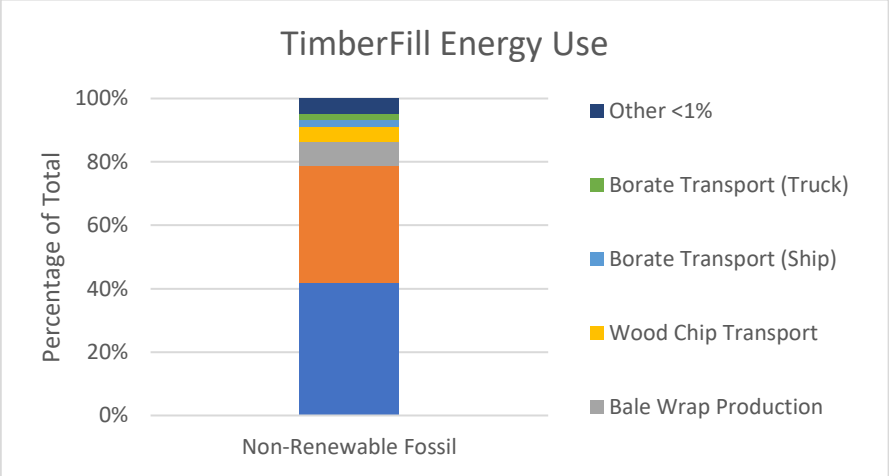


Diagram A. 20: TimberFill Non-Renewable Energy Use

Diagram A.8 illustrates the use of renewable energy, specifically hydropower, for TimberFill in terms of percentage of the total value. Electricity transformation from high to medium energy made up most of the energy use with 76%. The second largest contributor is woodchip production making up 21% of energy use. Bale wrap production and other processes make up the last 3% of the energy use.

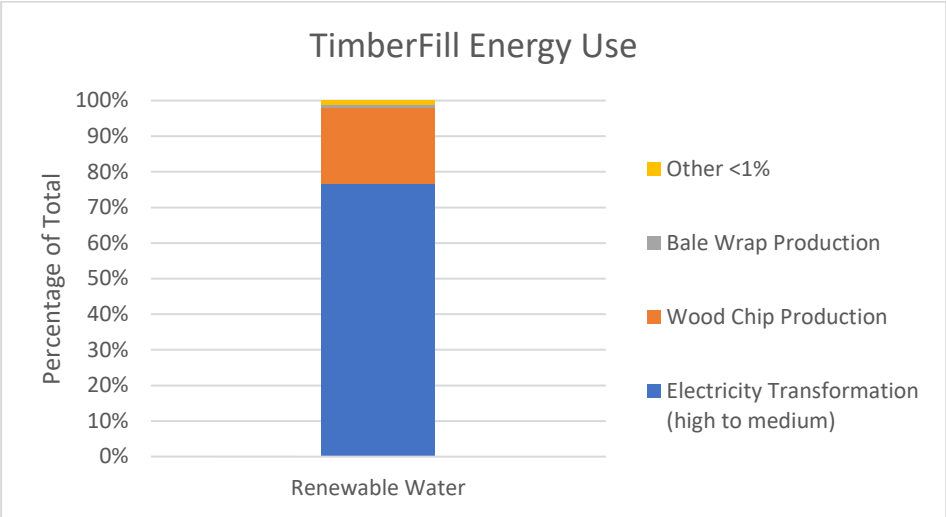


Diagram A. 23: TimberFill Renewable Energy Use, Water

A.3.1.6 Interpretation

A.3.1.6.1 TimberBoard Normalization

After normalization, the most harmful impact category is ecotoxicity at about 0.09% and eutrophication (0.04%) ranks second as shown in Diagram A.13. The normalization factors used were taken from US 2008 in openLCA which are listed in table 51.

Impact category	Normalization factor
Acidification	94.5501751778371
Carcinogenics	4.97525260101256E-5
Ecotoxicity	10975.0810784115
Eutrophication	20.7257919485728
Fossil fuel depletion	21286.9221664978
Global warming	24038.981612583
Non carcinogenics	0.00103279209996221
Ozone depletion	0.145783649998144
Respiratory effects	29.5590347721844
Smog	1447.95751113479

Table A. 13: Normalization factors

Treatment of spoil from both hard coal mining and lignite mining in surface landfill contributes the most to both ecotoxicity and eutrophication. PMDI production is one of the major contributors to eutrophication. Even though acidification and GWP have high emissions by amounts, they were only ranked the fourth and the sixth compared to other TRACI 2.1 impact categories after dividing normalization factor in diagram 45 orange line below.

A.3.1.6.2 TimberFill Normalization

For TimberFill, the severe impact categories are fossil fuel depletion (0.005%) and eutrophication (0.003%) ranked in Diagram A.9. The top three contributions for fossil

fuel depletion are natural gas production, ethylene production, and petroleum and gas production. Other than treatment of spoil from lignite mining and coal mining, treatment of wastewater and petroleum production were in the top five contributions to eutrophication. GWP exhibits the second highest amount of emissions in blue column, but GWP was only ranked the fourth compared to other impact categories required by EN15804+A2 in orange line.

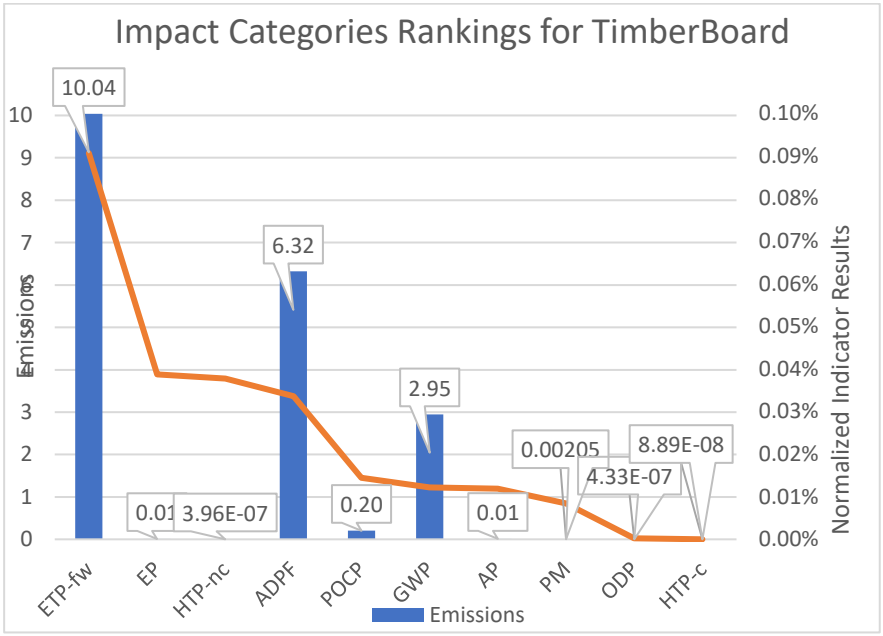


Diagram A. 26: TimberBoard Ranked Environmental Impacts

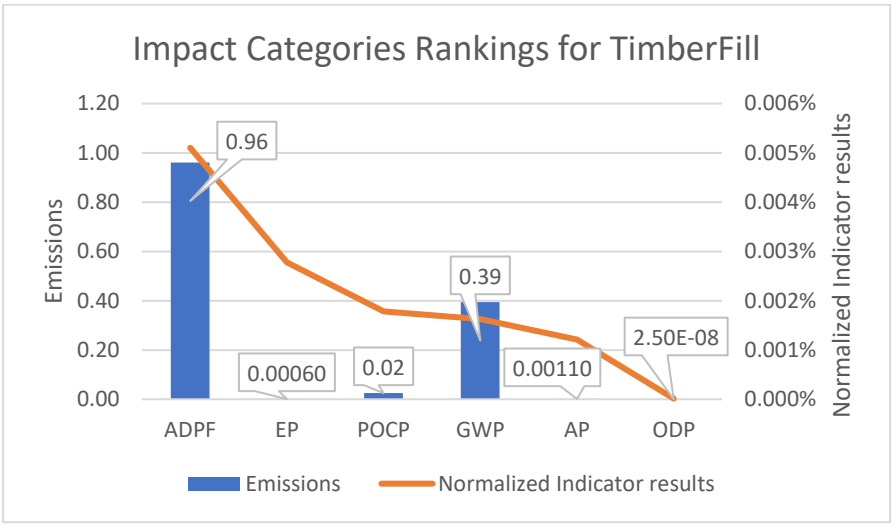


Diagram A. 29: TimberFill Ranked Environmental Impacts

- **Eutrophication**

Eutrophication is known as a midpoint category and affects ecosystem health and infrastructure health. Eutrophication is a leading cause of impairment of many freshwater and coastal marine ecosystems in the world (Chrislock et. Al., 2013).

Eutrophication has become a global aquatic environmental problem because of its ecological consequences, such as frequent outbreaks of algal blooms threatening the reliable supply of drinking water. Eutrophication increases biological oxygen demand

(BOD) of water, releases toxic gases, encourages profuse growth of aquatic weeds which negatively affect fish growth, fish spawning, domestic use and navigation. Eutrophic water promotes the growth of disease-causing agents which lead to health hazards. Increasing rates of silt and organic debris deposits in eutrophic water bodies makes them shallower. Over time the body of water into a wetland and eventually dry land which ultimately leads to water crisis of the environment (Jahani 2018).

The known consequences of cultural eutrophication include blooms of blue-green algae, tainted drinking water supplies, degradation of recreational opportunities, and hypoxia. Cultural eutrophication refers to the addition of human water pollutants such as sewage, detergents, and fertilizers which increases the aging process of algae. The estimated cost of damage mediated by eutrophication in the U.S. alone is approximately $2.2 billion annually (Dodds et al. 2009).

Eutrophication is a global aquatic environmental problem. At the global level, eutrophication can be minimized through sustainable management and conservation of water resources. Eutrophication potential can be decreased by controlling waste discharges and utilizing effective wastewater treatment (Jahani 2018). For both TimberBoard and TimberFill, the main contributors to eutrophication occur upstream during material manufacture, mainly of PMDI adhesive. The use of adhesives with less eutrophication potential would be the most effective way to decrease eutrophication potential of TimberHP's products.

- **Fossil Fuel Depletion**

When fossil fuels are burned, they emit greenhouse gases like carbon dioxide that trap heat in the earth's atmosphere and contribute to climate change. In 2019, fossil fuels accounted for 74 percent of U.S. greenhouse gas emissions. Nearly 25% percent of emissions in the United States come from fossil fuels extracted from public lands.

Fossil fuels are a nonrenewable resource that contribute greatly to environmental impacts such as greenhouse gas emissions. Switching from the use of fossil fuels to renewable energy is the most effective way to decrease fossil fuel depletion. In the case of TimberHP, onsite power is generated by renewable sources, hydropower electricity. The use of fossil fuels comes mainly from upstream processes which are out of TimberHP's control. Natural gas is used onsite to generate heat used for manufacturing, which is the second highest contributor to fossil fuel depletion. Replacing natural gas with a cleaner or renewable energy source is one way that TimberHP could greatly reduce their contribution to fossil fuel depletion. Another alternative could be heat integration. The need for natural gas could be decreased or eliminated by using waste heat from dryers or other manufacturing processes.

- **Ecotoxicity**

Ecotoxicity is classified as a midpoint category, meaning it causes physical changes or environmental issues. Ecotoxicity contributes ecosystem health and infrastructure health which are endpoint categories that describe system-wide damages such as loss of biodiversity or economic corrosion damage (Lecture 15, p.9). For 5.65 kg TimberBoard production with 0.28 PMDI use, an estimate potentially affected fraction of species (PAF) integrated over time and volume was about 10 CTUe (comparative toxic unit) for freshwater ecotoxicity potential. 81% of ecotoxicity emitted in the upstream PMDI productions. Only 9% might occur in municipal solid waste (0.008 kg)

process might occur onsite if wood chips could not be fully recirculated back as wood chip inputs after trimming. Ecotoxicity should not be considered when conducting EPDs if no board solid waste is produced in the entire manufacturing process. The USEtox indicator substance could be benzene. It is optional to care about Ecotoxicity based on EN15804 + A2.

A.3.1.7 Sensitivity Analysis

A.3.1.7.1 Raw Material Production and manufacturing

As our report shows, the advantages of wood insulation lie in the fact that it uses softwood chips, dependent product from lumber production, which contributes to the environmental impact of the of the products. Alongside the many positive qualities that these insulation products provide, the product will outrank its competitors in environmental awareness and function. This analysis aims to compare the carbon footprint of TimberHP's wood insulation with similar wood fiber insulation competitors.

A.3.1.7.2 Wood Fiber Board Comparisons with Other Manufacturers

TimberBoard compares well to other competing wood fiber insulation products. Most wood fiber insulation products are below 2021 Carbon Leadership Forum (CLF) baseline of about 20.7 kg CO_2 eq except Knauf Heraklith homogeneous board. Knauf Heraklith use only 33% spruce wood and 51% cement as adhesive as shown in diagram A. 11-(a). This study found out that TimberBoard has shown a similar GWP as Beton Wood Fiberthem as in diagram A.11-(b). TimberBoard has a similar material composition as Gutex but 1% more adhesive. STEICO used more hydrophobic agents with less wood content. Beton Wood added 6% recycled paper into their Fibertherm according to IBU EPD in 2016. Knauf has a much smaller wood content, so the biogenic carbon could not break even with the carbon emissions. This shows that products with a greater content of wood will have more carbon sequestration which helps to offset their carbon emissions, decreasing their global warming potential.

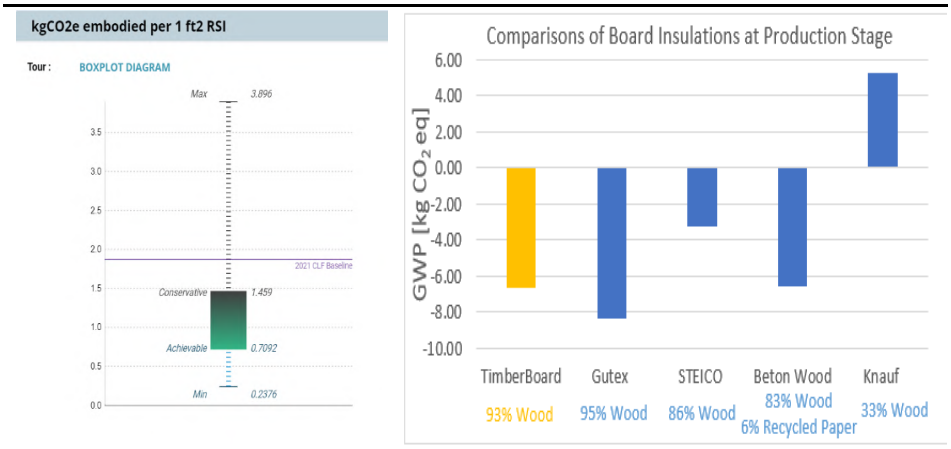


Diagram A. 32: Wood fiber board insulation EPD uncertainty comparisons (a) EC3 boxplot of embodied carbon kg CO_2 eq per 1 ft2 RSI (b) Compare TimberBoard GWP in kg CO_2 eq per 1 m2 RSI with other manufacturers

A.3.1.7.3 GWP Changed in Three Scenarios

The openLCA models were compared under three scenarios as demonstrated in diagram A.12. The original model used rest of world electricity providers for material production, meaning the electricity grid used global averages.

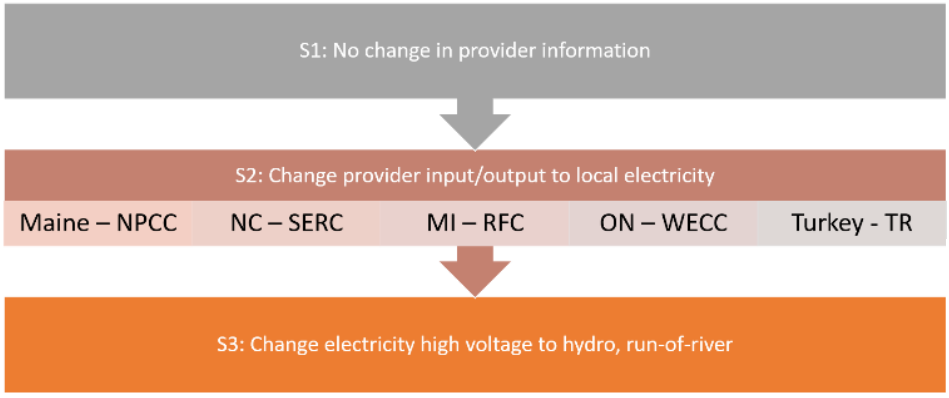


Diagram A. 35: Diagram flow for three scenarios

For scenario 2, the electricity provider was changed to local grids. Hydroelectricity of "electricity production, hydro, run-of-river | electricity, high voltage | Cutoff, U" was implemented in Scenario 3 because TimberHP bought RECs from nearby hydropower plants as shown in Figure A.11.



Figure A. 32: Hydropower plant near TimberHP on the left (Reference: Author)

For both TimberBoard and TimberFill in Diagram A.13 and 50, the GWP has similar trends at production stage from A1 to A3 (Our World Data n.d.). At A1 raw materials supply stage of all 3 scenarios were negative due to biogenic carbon from wood. A2 transportation contributed less than 3% of GWP. Most carbon emissions were coming from A3 manufacturing stage. The carbon emissions of A3 was slightly increased for Scenario 2 and decreased by half with hydroelectricity in Scenario 3. Hydroelectricity contributed to zero carbon emissions. Therefore, most GWP at A3 is natural gas in Scenario 3.

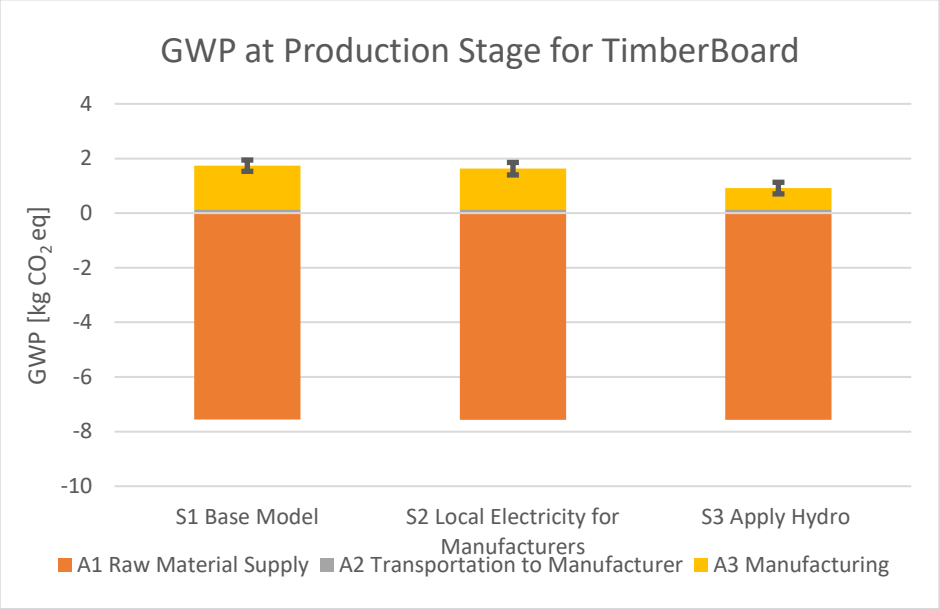


Diagram A. 38: GWP from A1-A3 for TimberBoard

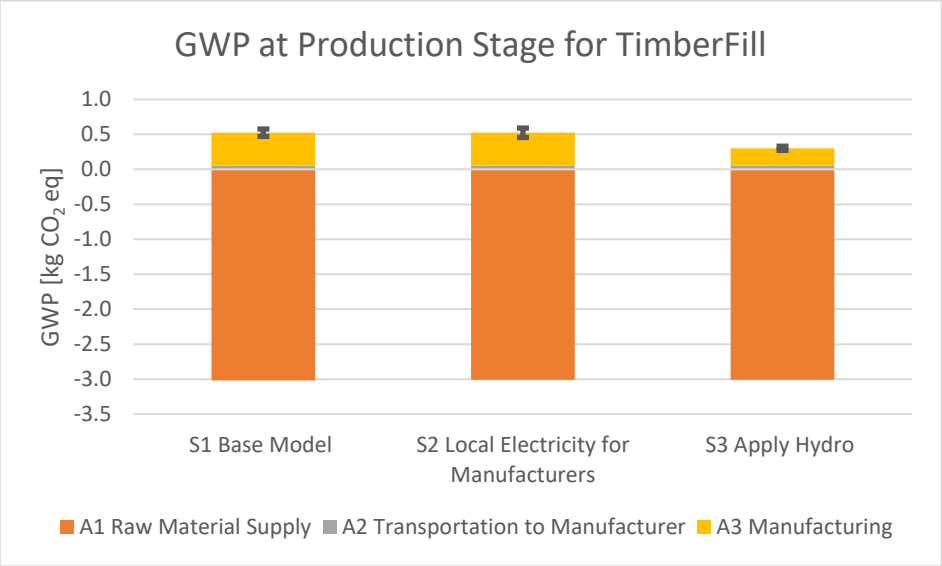


Diagram A. 41: 6 14: GWP from A1-A3 for TimberFill

Comparing S1 and S2, the A1 carbon emissions differ slightly because the carbon intensity of the grids varies in different countries as illustrated in diagram A.15. The GWP from wood chip production in Scenario 2 slightly increased by 1-3% because the US electricity grid has more carbon intensity than Canada's grid. 60% electricity production in Canada is from hydropower when the U.S. has only 6% hydropower but 38% natural gas and 22% coal in 2021 (Our World Data n.d.). STEICO manufactures their wood fiber insulation in Poland with 70% electricity from coal. The dirty grid might be one of the reasons why STEICO board insulation has higher GWP than other wood fiber board insulations.

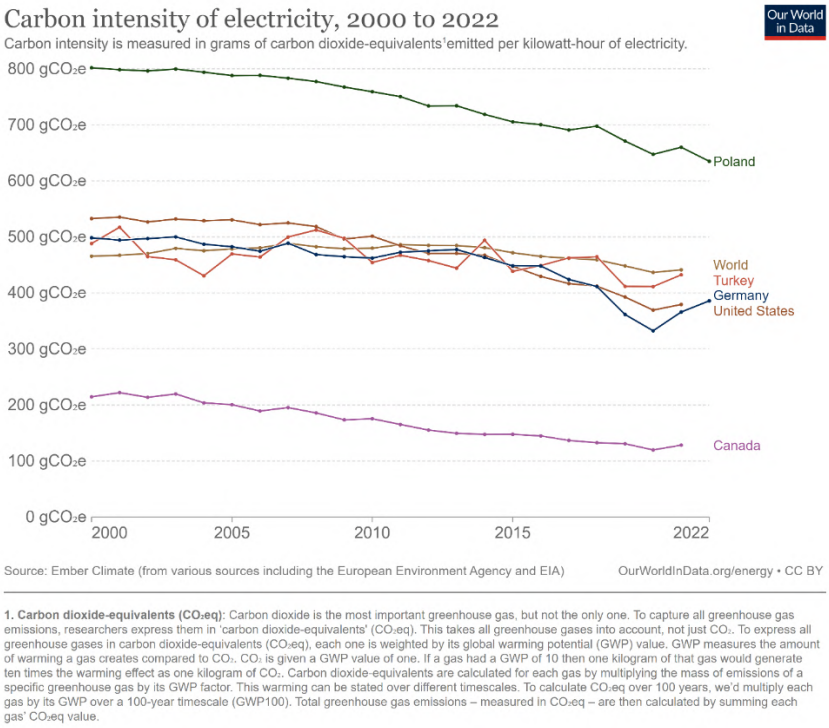


Diagram A. 44: Carbon intensity of electricity grids in relevant countries

A.3.1.8 Assessment of Data quality

Most of the data used was projected data assuming 90% efficiency provided by GO Lab at Madison, ME facility where they are not under full production. The annual gas input was based on plant natural gas consumption estimates conducted by Stantec. The wood chip production data was extrapolated from average Swiss conditions and adjusted for calculation year 2019. Additionally, transport data was based on a paper written in 2005. This study referenced the "paper production, woodcontaining, lightweight coated | paper, woodcontaining, lightweight coated | Cutoff, U" outputs from European production of lightweighted paper. A data quality assessment has been conducted below to evaluate uncertainty of inventory data collected for this study. The indicator score has been rated from 1 to 5 for good data and unknown data respectively.

Data Quality Indicators	Indicator Score
Reliability	3
Completeness	4
Temporal correlation	5
Geographical Correlation	5
Further technological correlation	3

Table A. 28: Pedigree matrix for life cycle inventory data

According to Monte Carlo Simulation, TimberBoard models have standard deviations about 0.207, 0.229, 0.213 for S1, S2, and S3 respectively using iterations of 100 as graphed in Diagram A.16; TimberFill models have standard deviations of 0.053 (S1), 0.067 (S2) and 0.03 (S3). Compared with 1000 iterations, the number was slightly changed by 0.002 for TimberBoard S3 as shown in 18. The result shows a normal

distribution slightly shift left. 95% of the probability distribution shows a standard deviation of approximately 0.2 for TimberBoard.

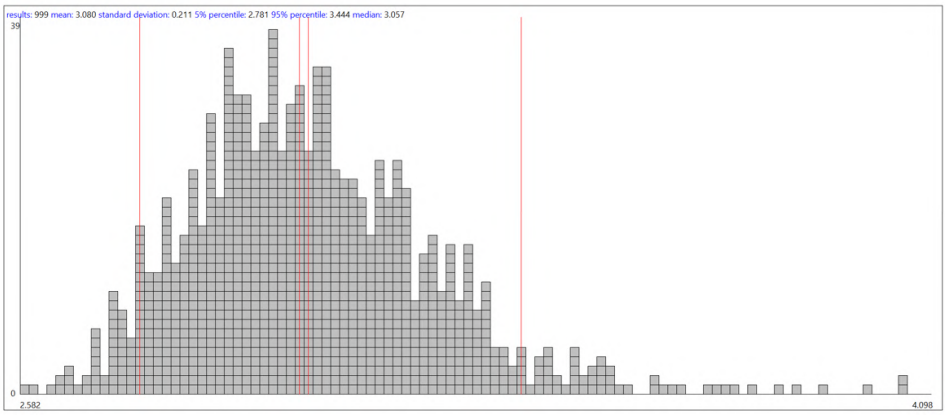


Diagram A. 47: Monte Carlo Simulation for TimerberBoard S3 GWP with 1000 Iterations

A.3.1.9 Conclusions

From the results of the study, we can conclude that wood insulation products are a great addition to the insulation market in North America. Between the countless insulation benefits the products entails and the fact that it is carbon negative, TimberHP's products provide a well-rounded product to their customers. Although the product sounds perfect, small flaws appear when compared to its German counterpart GUTEX. GUTEX, like TimberHP, produces wood-based insulation products with a global warming potential value just under –8 kg CO_2 equivalence. When compared to TimberHP's global warming potential, which is nearing –7 kg CO_2 equivalence, you can see that there are improvements that can be made.

When the product composition is compared side by side, the obvious difference is the amount of wood used in the manufacturing process. GUTEX utilizes 95% wood chips while TimberHP uses 93% meaning the German company's products have more biogenic carbon overall. GUTEX also uses less adhesive in their product, contributing less to acidification. Another contributing factor to TimberHP's higher carbon equivalence is that Germany uses cleaner natural gases than that of American natural gases. A large portion of Germany's natural gas is imported from either Norway or the Netherlands which have high quality natural gas. Germany is also ranked as the top country for the best gas due to its regulation of emissions including sulfur limits. America imports 99% of their natural gas from Canada which is brought straight through pipelines.

Taking these points into account, TimberHP has room to improve its global warming potential. Our team recommends the following changes to improve the global warming potential as well as acidification values:

1. Use more wood chips and less alternative adhesive in all TimberHP production.
2. Use renewable (cleaner) natural gas for heat production or recycle heat waste from another process in procedure.

Further improvements can be made in future studies as well. Due to our time and resource constraints, our study neglected some minor processes that would help complete the overall analysis. Packaging transportation as well as filtered and sanitary

sewer usage were both neglected from this study. Another possible test that can be done is an air and water quality test for dangerous and hazardous substances. Applying this study as well as these neglected processes would provide TimberHP with a full analysis of their product. Following the recommended improvements, TimberHP's products can match that of GUTEX's German based wood insulation in quality and environmental awareness.

Synergistic Impact of Teamwork in Sustainable Project Analysis: The experience of collaborating on the life cycle assessment of Timber work with my colleagues proved to be profoundly impactful. Working as a team not only facilitated a mutual exchange of knowledge and ideas but also fostered a synergistic environment where each member's unique strengths were harnessed to enhance the project's overall quality. The collective endeavor allowed for a more nuanced understanding of the complexities involved in sustainable material assessment, culminating in a comprehensive and detailed analysis. This teamwork experience emphasized the importance of collaborative effort in achieving rigorous academic and practical objectives, ultimately leading to a project outcome that was both educational and professionally enriching. The success of this teamwork project underlines the value of cooperative engagement in addressing the multifaceted challenges of sustainable development, highlighting the potential for collective contributions to yield substantial and meaningful advancements in the field.



Figure A. 35: Visiting Factory with team



Figure A. 38: Presenting the final results

A.3.2 Second Semester: Sustainable Design and Technologies In construction

Engaging in the "TREND project" afforded me the opportunity to enroll in a course within the Department of Architecture in second semester, thereby enhancing my understanding of sustainability and facilitating the practical aspects of my thesis. This experience proved invaluable as it provided insights into the latest achievements in the United States, enabling a comparative analysis of research conducted in Europe by researchers addressing climate change issues. Integral to the thesis-writing process is the formulation of pertinent research inquiries and the subsequent establishment of a methodological framework for their resolution. This course played a pivotal role in guiding me to articulate cogent questions germane to the thesis title, facilitating the development of an apt and practical investigative framework.

The course on "Sustainable Design and Technologies in Construction: Sustainable Building Systems" during the previous semester provided a comprehensive exploration of various aspects related to sustainable building practices. The curriculum delved into the intricate calculations and analyses integral to sustainable construction, and my academic engagement culminated in a detailed assignment covering diverse facets of sustainable building systems. The assignment focused on conducting a thorough Life Cycle Assessment (LCA) of materials and structural systems, encompassing considerations such as environmental impact, resource consumption, and overall sustainability. Furthermore, the evaluation extended to Indoor Environmental Quality (IEQ), examining parameters vital for creating healthy and comfortable living spaces. The assessment also delved into water footprint analysis, addressing the conservation and responsible use of water resources in building processes. A critical component of the assignment involved the examination of Life Cycle Costs (LCC), aiming to understand the economic implications of sustainable building practices over the entire lifespan of a structure. The multifaceted analysis encapsulated a holistic approach to sustainable design and technologies, encompassing environmental, social, and

economic dimensions. This academic endeavor provided invaluable insights into the intricate interplay between various elements in sustainable construction, fostering a deeper understanding of the complexities and considerations inherent in designing and implementing eco-friendly building systems. The experience not only enhanced my knowledge but also instilled a heightened awareness of the profound impact sustainable practices can have on the construction industry. This course presented various theoretical frameworks for measuring sustainability in the constructed environment and introduced technical skills necessary for work on sustainable buildings. Throughout the semester, I compared different definitions of sustainability, evaluated claims of sustainable performance, and integrated this knowledge into a sustainable design process. The course focused on fundamental questions about sustainability, addressing how to identify and measure sustainability and how to design and build to achieve it. The interaction between quantitative and qualitative aspects of sustainability was explored from multiple perspectives, emphasizing the contributions and learning opportunities of each participant.



Figure A. 41: course title, Reference: Northeastern student Hub

A.3.2.1 Cours Description:

The course covered the theory of sustainability and green building procedures, focusing on sustainable design and construction practices. It explored the use of appropriate materials and systems with low environmental impacts, aimed at creating energy-efficient buildings. The curriculum also included green construction practices, such as reducing pollution, emissions, and construction waste. Furthermore, it examined the U.S. Green Building Council's LEED rating system, providing valuable insights for students preparing for the LEED Green Associate examination.

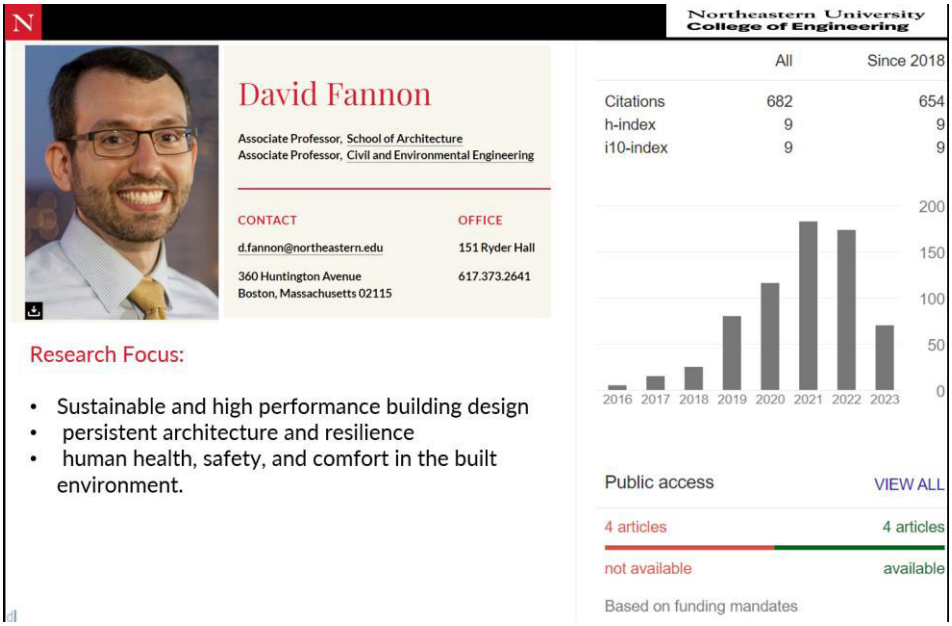


Figure A. 44: professor Fannon Background research

A.3.2.2 Course overview

This course provided several theoretical frameworks for measuring sustainability within the constructed environment and introduced the technical skills necessary for working on sustainable buildings, whether in practice or as part of further study in the Master of Science in Sustainable Building Systems program and related fields. By the conclusion of this course, students were able to compare and contrast various definitions of sustainability, evaluate claims of sustainable performance, and integrate this knowledge into a sustainable design process. To address the comprehensive scope of sustainability in the built environment, the course consistently posed two fundamental questions of sustainability: How can we determine if something is sustainable? And, assuming that identification or measurement is possible, how do students proceed with designing and constructing to achieve sustainability? In exploring these intertwined questions, particular attention was paid to the interaction between quantitative (e.g., measurement, calculation, simulation) and qualitative (e.g., perception, motivation, values) aspects of sustainability. The approach to both questions was multi-perspective, recognizing that each participant had both contributions to make and learning to achieve, as we navigated through the technical and theoretical issues.

The course was structured as a graduate seminar, where learning occurred through preparation and participation. This structure necessitated that success depended on the experience, flexibility, and hard work of each participant. The course was divided into modules, each encompassing a specific set of tools for measuring or evaluating sustainability, along with strategies for creating sustainable buildings. These modules included a variety of learning methods such as contemporary and historic readings, lectures from the instructor and guests, class discussions, and diverse assignments, tailored to student interest and prior knowledge. Key components of the course included:

- Assignments/Exercises: Focused on multiple aspects of sustainability, these ranged from in-class exercises to homework, with students completing seven

assignments of one to two weeks' duration each. The lowest-scoring assignment was dropped, with detailed requirements and deadlines provided for each.

- Preparation and Contribution: Emphasizing the seminar format, it was imperative for students to be punctual, attentive, and actively engaged in discussions for the entirety of each class.
- The LEED Project: Students worked individually on an in-depth assessment of a specific credit from the USGBC LEED rating system, culminating in a written report that was substituted for a final exam.

The course's flexible module structure allowed for adjustments based on class feedback and discussions, with the instructor refining the schedule to accommodate student needs and interests. This instructional model, open-ended compared to traditional courses, offered students concrete opportunities to develop their understanding through experiential learning and feedback. Table 53 shows some of the topics, tools, and strategies.

#	Topic	Tools (measure)	Design Strategies (make)
1	Sustainable Design Metrics	Rating Systems	Integrated Design Process
2	Natural Resource and Sites	Footprint calculators	Water Conservation
3	Energy Accounting	Building Simulation	Envelopes and Passive design
4	Material Sustainability	Life Cycle Assessment	Materials and Resources
5	Financial sustainability	Life Cycle Cost Benefit Analysis	Lighting and Efficient systems
6	Human Health and Comfort	Post Occupancy Evaluation	Indoor Environmental Quality

Table A. 15: Topics, Tools, Design strategies

A.3.2.3 Some Activities

- Presenting different subject about sustainability and green building certificates by students:



Figure A. 47: weekly class session

- weekly discussing with different student around all subject related to sustainability:



Figure A. 50: free discussion about sustainability and sharing experiences

- Participating in the workshop organized by Professor David Fannon:

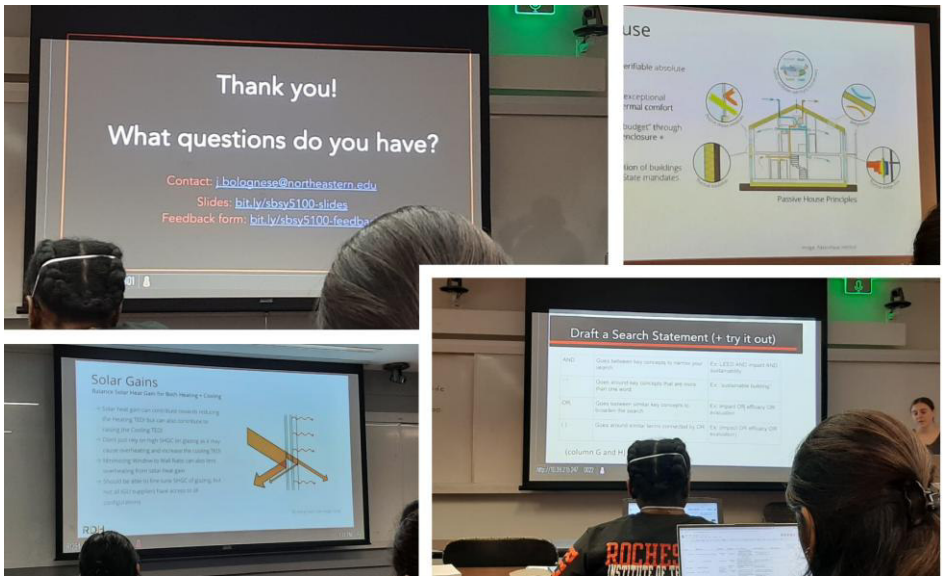


Figure A. 53: Workshop

- Presented carbon reduction strategies implemented by professional companies involved showcasing the methods and approaches these companies used to reduce their carbon footprint and mitigate climate change impact. The presentation typically included an examination of innovative technologies, sustainable practices, and policy initiatives that these organizations had adopted to decrease greenhouse gas emissions. It covered various sectors, from energy production and manufacturing to transportation and waste management, illustrating how these companies' integrated sustainability into their operations to achieve environmental and economic benefits.

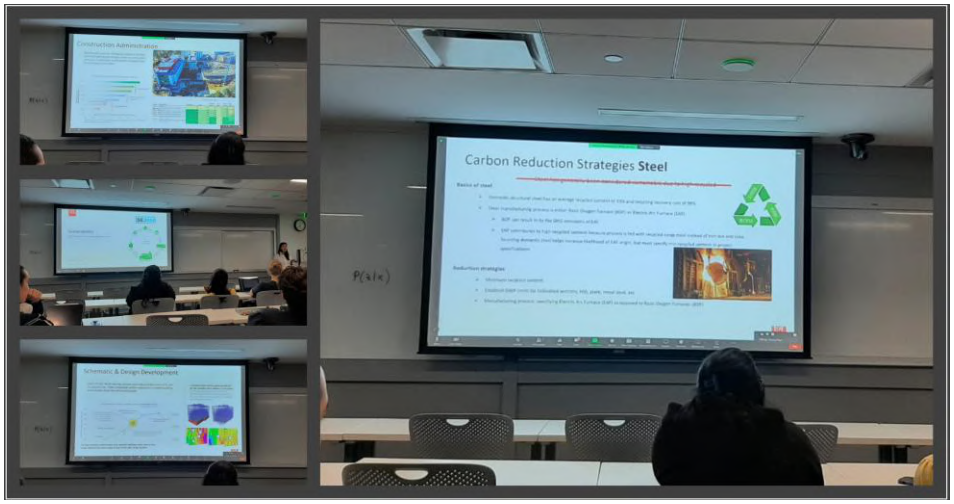


Figure A. 56: Presenting Carbon Reduction Strategies by professional

A.3.2.4 Assignments

Since the assignments conducted during this course provided useful and practical experience, they significantly influenced the development of the methodology and structure for my thesis. These assignments facilitated a comprehensive understanding of the subject matter, allowing for the formulation of a coherent and robust framework for my research. In the following sections, some of these assignments will be explained in detail, highlighting how they contributed to the refinement of my thesis approach and the establishment of a solid foundation for my investigative work. Each assignment's specific objectives, methodologies, and outcomes will be discussed to demonstrate their relevance and impact on my academic and research development. (First I have written the general question , then I have added my calculations and answers)

A.3.2.4.1 Assignment 1 Title: MATERIALS AND LIFE CYCLE ASSESSMENT

Overview of this section:
We discussed rating systems this semester that measure sustainability by evaluating the Drivers, Pressures, States, Impacts, or Responses of particular systems to see if buildings and products are sustainable. In the last module we introduced simulation tools as a way systematically compare the performance of alternatives, which is useful for assessment and in design, although limited to the single dimension of energy. One could argue that measuring sustainability lies in systematically understanding all the impacts: measuring the consequences of an action in terms of human health, societal benefits and environmental effects etc. This approach, which resembles the consequentialist ethical theory of utilitarianism, is particularly well suited to looking at material choices, and one method used to "sum up" the good and bad consequences is Life Cycle Analysis (LCA). While other courses in engineering cover LCA in detail, this assignment focuses on applying LCA to building design problems. It stands to reason that a Sustainable Building must be made from Sustainable materials, so in this module of the course we will consider materials as a topic and LCA as a skill necessary for sustainable buildings.

Explanation of assignments:

This assignment had two parts. First, at the scale of a single product, it could be done in pairs. Second, at the scale of building systems, it was done individually. For the first, we studied a product or material and posted a video to the course website. For the second, we conducted a simple LCA, wrote a very brief report, and submitted a PDF as an assignment by the deadline.

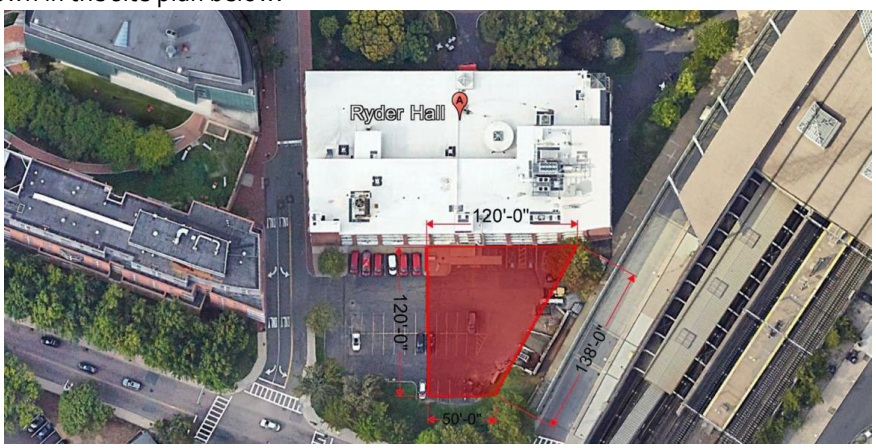
Part One: Product Research: (In teams of 2)

We (and a partner) should have done a quick but deep dive into the human and environmental consequences of a product (or material) that might be suitable for our ongoing project of renovation or addition at Ryder Hall. We identified a building product (or material) we found interesting and learned more about its (claimed) environmental attributes, from the manufacturer's website, industry publications, etc. We were especially on the lookout for any Environmental Product Declarations (EPD) or other information about the environmental and human health effects of this product from the manufacturer's point of view. We also needed some background research to put this product in context of the state of the industry. I often started with buildinggreen.com for a general overview of the market, technology, and other products that serve a similar purpose, and to see if there were greener alternatives. Finally, we created a brief (not more than 2 minutes) recorded video/presentation including photos of the product (alone or in use) and a description of the environmental benefits and/or concerns, LEED credits, etc.we Imagined the campus leadership asked us about this product and we had only a short time to brief them on the merits and liabilities of choosing this product. We had to cite all sources, credit all images. We uploaded our video to a Canvas page so we could view others' presentations.

Part Two: Life Cycle Assessment of Building Design Alternatives. (Individual)

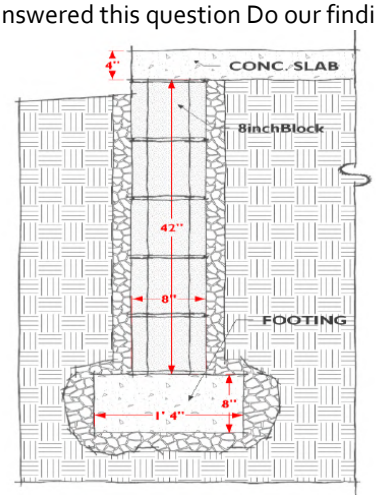
We downloaded and installed the Athena Impact Estimator for Buildings from the Athena Sustainable Materials Institute at http://www.athenasmi.org/. This was a C# application that ran on Windows and was available at no cost (registration required). Alternatively, this was installed in COE computer labs including the VLAB if we could not or did not want to install locally. Using the Impact Estimator, we analyzed the life cycle impacts of the scenarios outlined below. We compiled our results into a short-written report describing what we learned with words and graphics as appropriate. We provided a bill of materials for each design. We submitted this final report to the assignment below.

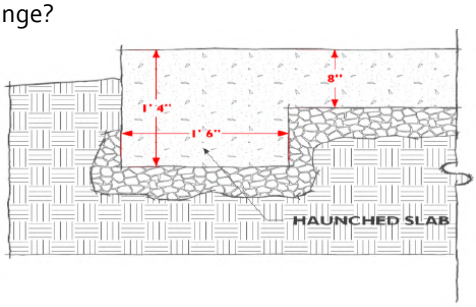
1. We should planed a two-story addition on the south side of Ryder (taking the place of the current parking lot). We were choosing between two equally effective foundation options for the proposed 10,000 square foot, single-story structure, with a footprint as shown in the site plan below.



One option was a 4-inch-thick slab on grade, with a ±42-inch high 8-inch concrete-block perimeter foundation wall supported on a continuous 8-inch thick by 16-inch-wide strip-footing. The other option was an 8-inch-thick concrete slab on grade with a simple, turn-down (hunched) slab edge as the footing. The turn-down edge measured 16-inches deep (8-inch slab plus 8 additional inches below the slab) and is 18-inches wide. The sketches details were as bellow.

1.Assuming the functional unit of this foundation is identical, which LCA Impacts are most relevant to consider in this situation? Why?
2.Conduct the inventory and assessment using Athena. Provide a bill of materials.
3.Analyze the results, reporting at minimum the Global Warming Potential of each option, identify a preferred choice.
4.Then we supposed could increase the use of fly ash in the cast-in-place concrete to 35% of the cementitious materials (you will need a custom mix). and we should answered this question Do our findings change?



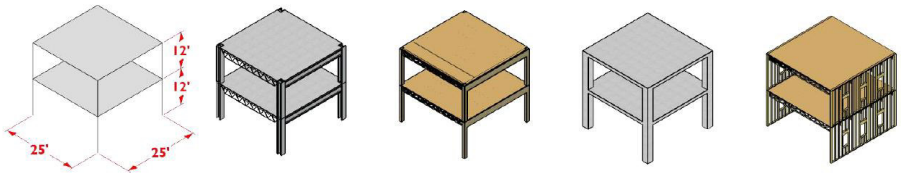


Although it was too early to have a structural design, as part of the concept design narrative you want to analyze the Life Cycle Impact of the load-bearing system for this two-story addition. Since the plan is not yet designed, our boss asked us to simulate a single hypothetical bay with four columns measuring 25x25 feet on each side, with a floor-to-floor height of 12-feet as suggested in the sketches below (fine details were not important, only the structure was.) we should Assumed 50 psf live loads to compare the following options based their impact at each stage in the life cycle.

1. Wide-Flange columns & beams supporting open-web steel joists & concrete topping slabs
2. Gluelam columns & beams and light-frame wood floor trusses supporting ¾" plywood floors
3. Concrete columns supporting a 2-way concrete slab floor
4. Wood Stud framing walls with light-frame wood floor trusses supporting ¾" plywood floors. Load-bearing walls on two sides are made of kiln-dried 2x6 with plywood sheathing.

we had to do : Conducting an inventory and provide a bill of materials. performing the assessment. Comparing fossil fuel use, smog potential, and eutrophication potential. What option seems best? Worst? Why? Are there other considerations not reflected here? Do we think this is a valid study? What is the functional unit, and has it been fairly

determined?



We had to Compile our calculations and results into a brief report/narrative that the design team can use to help your client (Northeastern!) make informed choices among this foundation and structural alternatives.

❖ Assignment's 1 Answer: Section 1

➢ **Project Description:**

- **W-F**: Wide-Flange columns & beams supporting open-web steel joists & concrete topping slabs
- **G-C**: Gluelam columns & beams and light-frame wood floor trusses supporting ¾" plywood floors
- **Concrete**: Concrete columns supporting a 2-way concrete slab floor
- **Wood Stud Framing**: Wood Stud framing walls with light-frame wood floor trusses supporting ¾" plywood floors. Load-bearing walls on two sides are made of kiln-dried 2x6 with plywood sheathing.

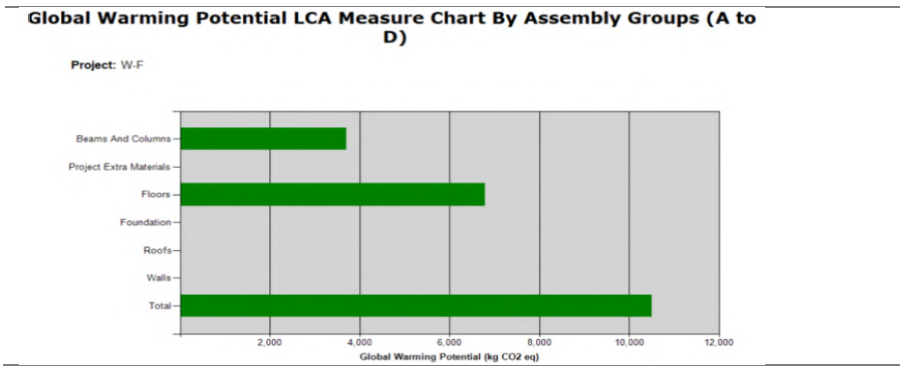
➢ **Project measures:**

- Area: 25*25
- Number of columns: 4 (per floor)
- Number of beam: 2 (per floor, depends on the model)
- Number of floors: 2

➢ **Analysis:**

- **Wide-Flange** columns & beams supporting open-web steel joists and concrete topping slabs.

The result shows that Floors have more critical role in Global warming issue (Table 6.20).



Assembly Group	Unit	Total
Beams And Columns	kg CO2 eq	3.46E+03
Floors	kg CO2 eq	7.66E+03
Foundation	kg CO2 eq	0.00E+00
Project Extra Materials	kg CO2 eq	0.00E+00
Roofs	kg CO2 eq	0.00E+00
Walls	kg CO2 eq	0.00E+00
Total	**kg CO2 eq**	**1.11E+04**

Table A. 16: Global Warming Potential LCA by Assembly Groups (A to D), wide-Flang

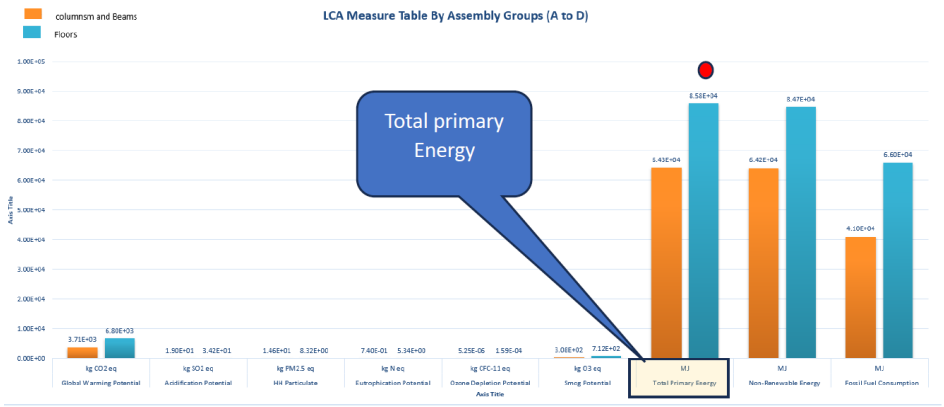


Diagram A. 50: LCA measure Table by Assembly Group (A to D),Wide-Flange)

The results demonstrate that, from an environmental impact perspective, generally, flooring plays a more important role than columns and beams.
Among all environmental Impacts categories Total primary Energy are the worth environmental pollution caused by Floor.

LCA Measures	Unit	Columns and Beams	Floors	Total
Eutrophication Potential	**kg N eq**	7.40E-01	5.34E+00	**6.08E+00**
Smog Potential	**kg O3 eq**	3.08E+02	7.12E+02	**1.02E+03**
Fossil Fuel Consumption	**MJ**	4.10E+04	6.60E+04	**1.07E+05**

Table A. 17: Other Environmental Impacts

To compare all result it is necessary doing Normalization, because different Unit.

- **G-C:** Glulam columns & beams and light-frame wood floor trusses supporting ¾" plywood floors.

Bill of Materials Report

Project: G-C

Material	Unit	Total Quantity	Columns & Beams	Floors	Foundations	Roofs	Walls	Project Extra Materials	Mass Value	Mass Unit
Galvanized Sheet	Tons (short)	0.1616	0.0000	0.1616	0.0000	0.0000	0.0000	0.0000	0.1616	Tons (short)
GluLam Sections	ft3	227.2937	227.2937	0.0000	0.0000	0.0000	0.0000	0.0000	3.3154	Tons (short)
Nails	Tons (short)	0.0132	0.0000	0.0132	0.0000	0.0000	0.0000	0.0000	0.0132	Tons (short)
Small Dimension Softwood Lumber, kiln-dried	Mbfm small dimension	1.9814	0.0000	1.9814	0.0000	0.0000	0.0000	0.0000	1.4306	Tons (short)
Softwood Plywood	msf (3/8")	2.6250	0.0000	2.6250	0.0000	0.0000	0.0000	0.0000	1.2213	Tons (short)

Table A. 18: Bill Materials Report , Project: G-C

The result shows that columns and Beams have more critical role in Global warming issue (Table A.19).

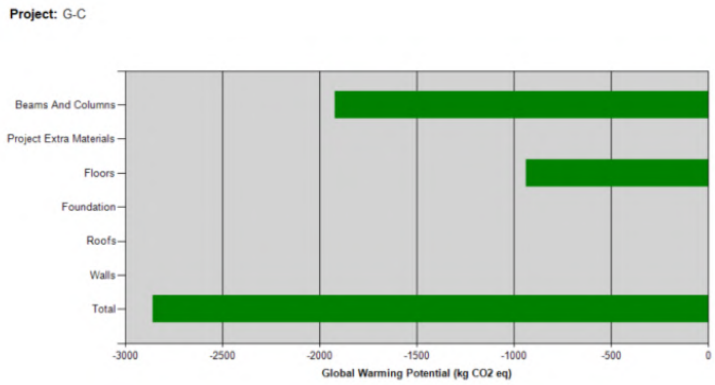


Table A. 19: Global Warming Potential LCA by Assembly Groups (A to D), G-C

Assembly Group	Unit	Total
Beams And Columns	kg CO2 eq	-1.92E+03
Floors	kg CO2 eq	-9.39E+02
Foundation	kg CO2 eq	0.00E+00
Project Extra Materials	kg CO2 eq	0.00E+00
Roofs	kg CO2 eq	0.00E+00
Walls	kg CO2 eq	0.00E+00
Total	**kg CO2 eq**	**-2.86E+03**

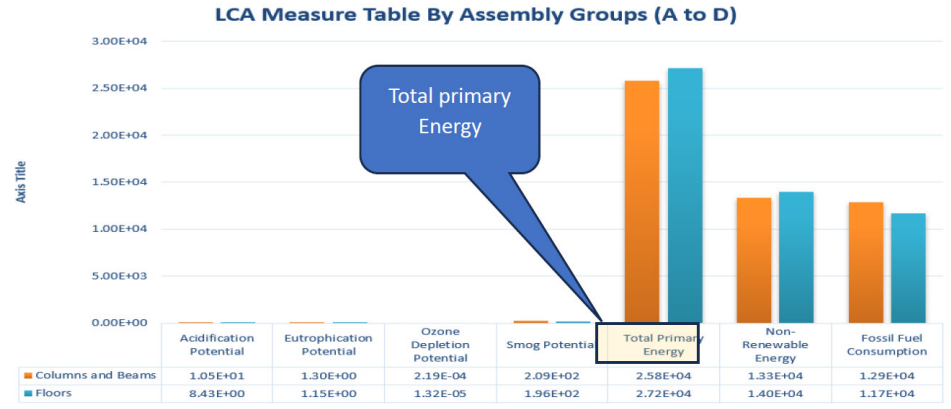


Diagram A. 53: LCA measure Table by Assembly Group (A to D), G-C

The results demonstrate that, from an environmental impact perspective, generally, flooring plays a more important role than columns and beams. Among all environmental Impacts categories Total primary Energy are the worth environmental pollution caused by Floor.

LCA Measures	Columns and Beams	Floors	Total
Acidification Potential	1.05E+01	8.43E+00	**1.90E+01**
Eutrophication Potential	1.30E+00	1.15E+00	**2.45E+00**
Ozone Depletion Potential	2.19E-04	1.32E-05	**2.32E-04**
Smog Potential	2.09E+02	1.96E+02	**4.06E+02**
Total Primary Energy	2.58E+04	2.72E+04	**5.30E+04**
Non-Renewable Energy	1.33E+04	1.40E+04	**2.73E+04**
Fossil Fuel Consumption	1.29E+04	1.17E+04	**2.46E+04**

Table A. 20: Other environmental impact categories, G-C

- **Concrete:** Concrete columns supporting a 2-way concrete

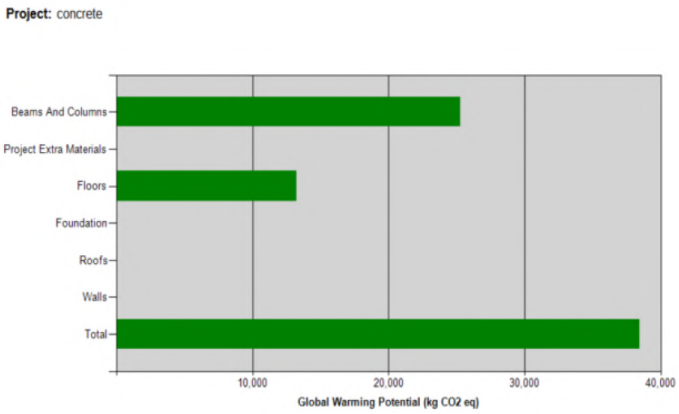
Bill of Materials Report

Project: concrete

Material	Unit	Total Quantity	Columns & Beams	Floors	Foundations	Roofs	Walls	Project Extra Materials	Mass Value	Mass Unit
1/2" Glass Mat Gypsum Panel	sf	1,374.9999	0.0000	1,374.9999	0.0000	0.0000	0.0000	0.0000	1.3936	Tons (short)
Concrete Benchmark USA 3000 psi	yd3	38.7081	0.0000	38.7081	0.0000	0.0000	0.0000	0.0000	74.8150	Tons (short)
Concrete Benchmark USA 4000 psi	yd3	36.3556	36.3556	0.0000	0.0000	0.0000	0.0000	0.0000	70.6681	Tons (short)
Rebar, Rod, Light Sections	Tons (short)	11.8853	10.2345	1.6508	0.0000	0.0000	0.0000	0.0000	11.8853	Tons (short)
Screws Nuts & Bolts	Tons (short)	0.0013	0.0000	0.0013	0.0000	0.0000	0.0000	0.0000	0.0013	Tons (short)

Table A. 21: Bill of Materials Report, Concrete

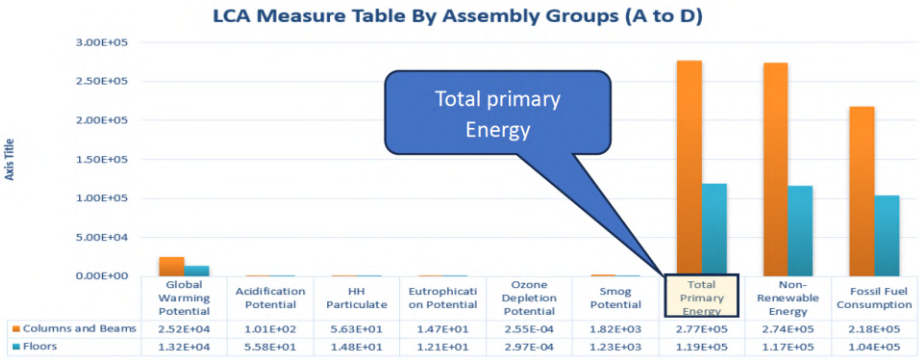
The result shows that columns and Beams have a more critical role in Global warming issue.



Assembly Group	Unit	Total
Beams And Columns	kg CO2 eq	2.52E+04
Floors	kg CO2 eq	1.32E+04
Foundation	kg CO2 eq	0.00E+00
Project Extra Materials	kg CO2 eq	0.00E+00
Roofs	kg CO2 eq	0.00E+00
Walls	kg CO2 eq	0.00E+00
Total	**kg CO2 eq**	**3.85E+04**

Table A. 22: Global Warming Potential LCA by Assembly Groups (A to D), Concrete

Diagram A. 19: LCA measure Table by Assembly Group (A to D), Concrete



The results demonstrate that, from an environmental impact perspective, generally, Beam and Columns plays a more important role than columns and beams.
Among all environmental Impacts categories Total primary Energy are the worth environmental pollution caused by Floor (Table A.23).

Table A. 23: Other environmental impact categories, Concrete

LCA Measures	Columns and Beams	Floors	Total
Global Warming Potential	2.52E+04	1.32E+04	**3.85E+04**
Acidification Potential	1.01E+02	5.58E+01	**1.57E+02**
HH Particulate	5.63E+01	1.48E+01	**7.10E+01**
Eutrophication Potential	1.47E+01	1.21E+01	**2.69E+01**
Ozone Depletion Potential	2.55E-04	2.97E-04	**5.51E-04**
Smog Potential	1.82E+03	1.23E+03	**3.06E+03**
Total Primary Energy	2.77E+05	1.19E+05	**3.96E+05**
Non-Renewable Energy	2.74E+05	1.17E+05	**3.91E+05**
Fossil Fuel Consumption	2.18E+05	1.04E+05	**3.21E+05**

- **Wood Stud Framing:** Wood Stud framing walls with light-frame wood floor trusses supporting ¾" plywood floors. Load-bearing walls on two sides are made of kiln-dried 2x6 with plywood sheathing.

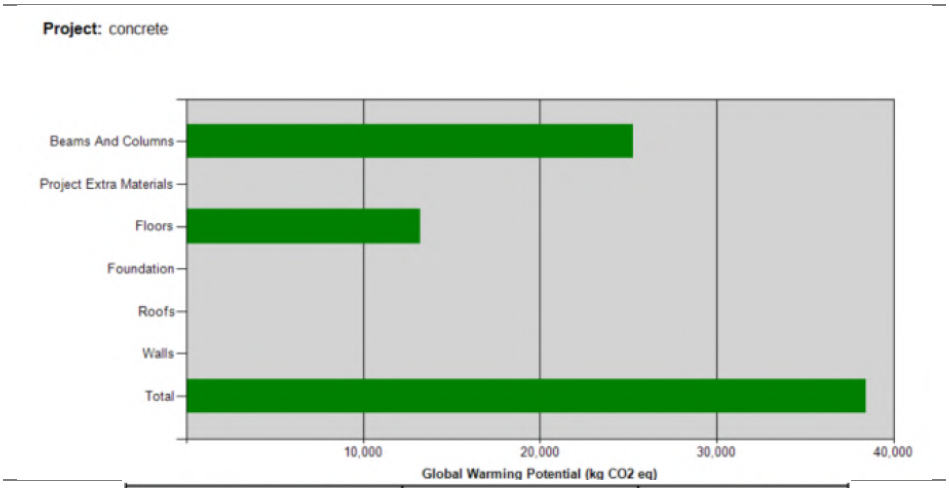
Table A. 24: Bill of Materials Report, wood Stud Framing

Bill of Materials Report

Project: wood stud framing

Units: SI / Imperial

Material	Unit	Total Quantity	Columns & Beams	Floors	Foundations	Roofs	Walls	Project Extra Materials	Mass Value	Mass Unit
Nails	Tons (short)	0.0161	0.0000	0.0132	0.0000	0.0000	0.0029	0.0000	0.0161	Tons (short)
Small Dimension Softwood Lumber, kiln-dried	Mbfm small dimension	2.1210	0.0000	1.7733	0.0000	0.0000	0.3477	0.0000	1.5314	Tons (short)
Softwood Plywood	msf (3/8")	3.0440	0.0000	2.6250	0.0000	0.0000	0.4190	0.0000	1.4162	Tons (short)
Steel Tubing	Tons (short)	1.0605	0.0000	1.0605	0.0000	0.0000	0.0000	0.0000	1.0605	Tons (short)



Assembly Group	Unit	Total
Beams And Columns	kg CO2 eq	2.52E+04
Floors	kg CO2 eq	1.32E+04
Foundation	kg CO2 eq	0.00E+00
Project Extra Materials	kg CO2 eq	0.00E+00
Roofs	kg CO2 eq	0.00E+00
Walls	kg CO2 eq	0.00E+00
Total	**kg CO2 eq**	**3.85E+04**

Table A. 25: Global Warming Potential LCA by Assembly Groups (A to D), Wood Stud Framing

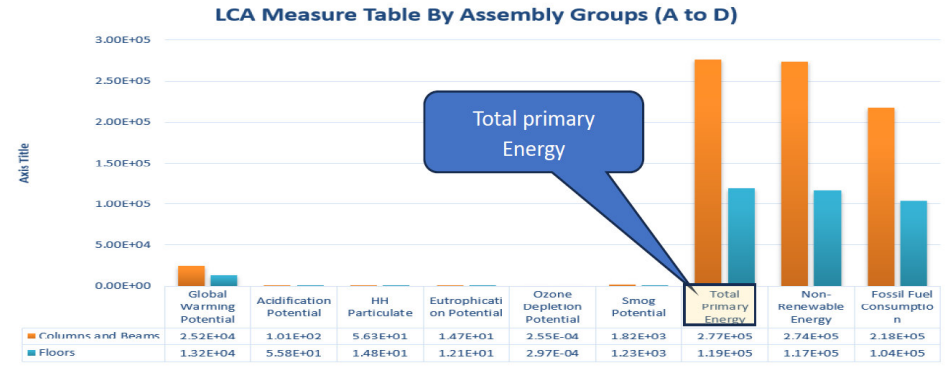


Diagram A. 60: LCA measure Table by Assembly Group (A to D), Wood Stud Framing

The results demonstrate that, from an environmental impact perspective, generally, Beam and Columns plays a more important role than columns and beams. Among all environmental Impacts categories Total primary Energy are the worth environmental pollution caused by Floor.

Table A. 26: Other environmental impact categories, Wood Stud Framing

LCA Measures	Columns and Beams	Floors	Total
Global Warming Potential	2.52E+04	1.32E+04	**3.85E+04**
Acidification Potential	1.01E+02	5.58E+01	**1.57E+02**
HH Particulate	5.63E+01	1.48E+01	**7.10E+01**
Eutrophication Potential	1.47E+01	1.21E+01	**2.69E+01**
Ozone Depletion Potential	2.55E-04	2.97E-04	**5.51E-04**
Smog Potential	1.82E+03	1.23E+03	**3.06E+03**
Total Primary Energy	2.77E+05	1.19E+05	**3.96E+05**
Non-Renewable Energy	2.74E+05	1.17E+05	**3.91E+05**
Fossil Fuel Consumption	2.18E+05	1.04E+05	**3.21E+05**

- **Comparison different systems:**

Comparison of Smog Potential:

The results show smog potential by all the projects in the cradle to the gate stage is more critical, while this problem is more critical in the case of the third project, which has concrete columns and beams (Table A.27).

Table A. 27: Comparison of smog potential by life cycle stage

Project Name	Unit	Product (A1 to A3)	Construction Process (A4 & A5)	Use (B2 & B4)	Total Operational Energy (B6)	End of Life (C1 to C4)	Beyond Building Life (D)	Total
concrete	kg O3 eq	1.49E+03	8.09E+02	0.00E+00	0.00E+00	6.39E+02	1.21E+02	**3.06E+03**
G-C	kg O3 eq	2.48E+02	7.33E+01	0.00E+00	0.00E+00	8.72E+01	-2.63E+00	**4.06E+02**
W-F	kg O3 eq	5.73E+02	2.98E+02	0.00E+00	0.00E+00	1.63E+02	-1.43E+01	**1.02E+03**
wood stud framing	kg O3 eq	1.71E+02	6.74E+01	0.00E+00	0.00E+00	5.17E+01	-5.10E+00	**2.85E+02**
Total	**kg O3 eq**	**2.48E+03**	**1.25E+03**	**0.00E+00**	**0.00E+00**	**9.42E+02**	**9.92E+01**	**4.77E+03**

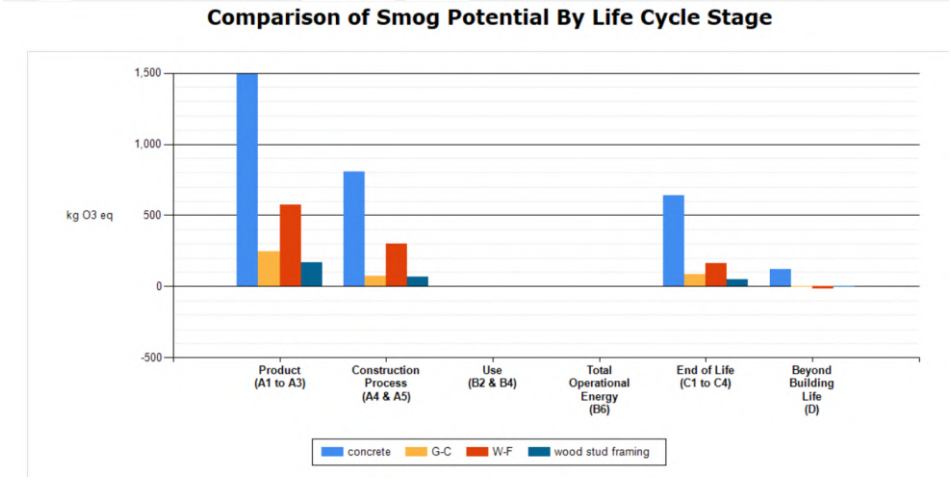


Diagram A. 63: Comparison of smog potential by life cycle stage

Project Wood Stud Framing (Wood Stud framing walls with light-frame wood floor trusses supporting ¾" plywood floors. Load-bearing walls on two sides are made of kiln-dried 2x6 with plywood sheathing) is best one in terms of least smog potential. (Diagram A.23)

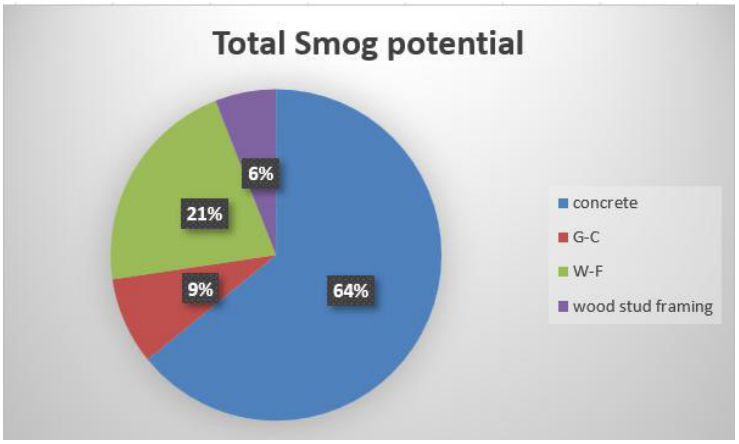


Diagram A. 66: Total Smog potential

Comparison of Fossil Fuel Consumption:

The findings indicate that fossil fuel consumption is more problematic for all projects in the product stage (cradle to the gate) of the life cycle, but it is more problematic for the third project with concrete beams and columns (Table A.28).

Project Name	Unit	Product (A1 to A3)	Construction Process (A4 & A5)	Use (B2 & B4)	Total Operational Energy (B6)	End of Life (C1 to C4)	Beyond Building Life (D)	Total
concrete	MJ	2.11E+05	3.88E+04	0.00E+00	0.00E+00	2.36E+04	4.82E+04	**3.21E+05**
G-C	MJ	1.72E+04	5.50E+03	0.00E+00	0.00E+00	2.93E+03	-1.04E+03	**2.46E+04**
W-F	MJ	9.14E+04	1.50E+04	0.00E+00	0.00E+00	6.39E+03	-5.69E+03	**1.07E+05**
wood stud framing	MJ	2.30E+04	4.06E+03	0.00E+00	0.00E+00	1.88E+03	-2.03E+03	**2.70E+04**
Total	**MJ**	**3.42E+05**	**6.34E+04**	**0.00E+00**	**0.00E+00**	**3.48E+04**	**3.94E+04**	**4.80E+05**

Table A. 28: Comparison of Fossil fuel consumption by life cycle

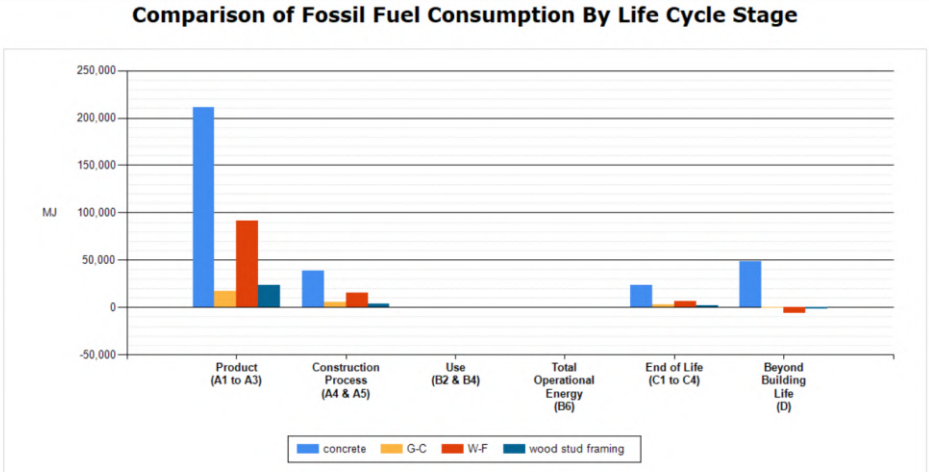


Diagram A. 69: Comparison of Fossil fuel consumption by life cycle stage

The pie chart shows that Project G-C (**Glulam columns & beams** and light-frame wood floor trusses supporting ¾" plywood floors) in general has least energy consumption (Diagram A.24).

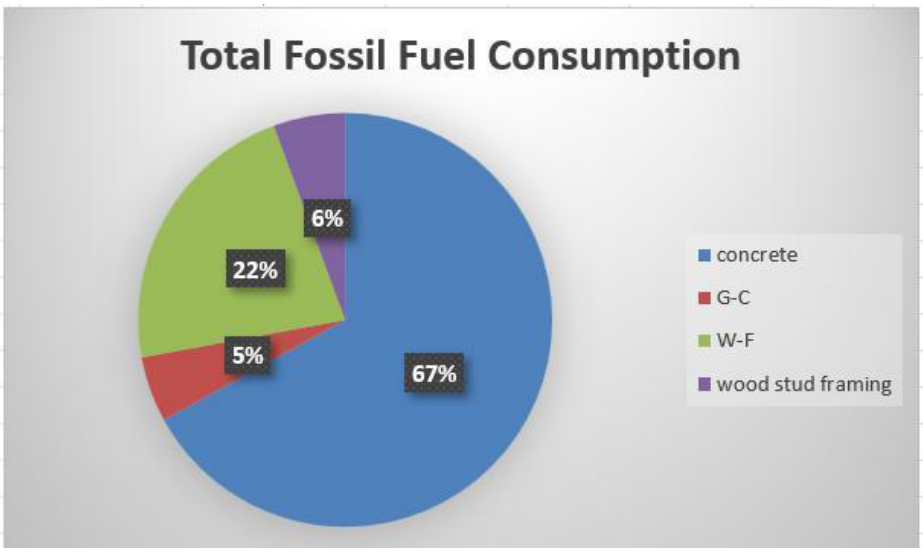


Diagram A. 72: Total Fossil Fuel Consumption

Comparison of Eutrophication potential:

The findings indicate that eutrophication potential is a more serious issue for all projects from the Cradle to the Gate stage, but it is especially serious for the third project since it contains concrete columns and beams.

Table A. 29: Comparison of Fossil fuel consumption by life cycle stage

Project Name	Unit	Product (A1 to A3)	Construction Process (A4 & A5)	Use (B2 & B4)	Total Operational Energy (B6)	End of Life (C1 to C4)	Beyond Building Life (D)	Total
concrete	kg N eq	2.25E+01	2.54E+00	0.00E+00	0.00E+00	1.22E+00	6.16E-01	**2.69E+01**
G-C	kg N eq	1.90E+00	4.05E-01	0.00E+00	0.00E+00	1.65E-01	-1.34E-02	**2.45E+00**
W-F	kg N eq	4.99E+00	8.43E-01	0.00E+00	0.00E+00	3.12E-01	-7.29E-02	**6.08E+00**
wood stud framing	kg N eq	1.06E+00	2.66E-01	0.00E+00	0.00E+00	9.82E-02	-2.60E-02	**1.40E+00**
Total	**kg N eq**	**3.04E+01**	**4.05E+00**	**0.00E+00**	**0.00E+00**	**1.79E+00**	**5.04E-01**	**3.68E+01**

Table A. 56: Comparison of Fossil fuel consumption by life cycle stage

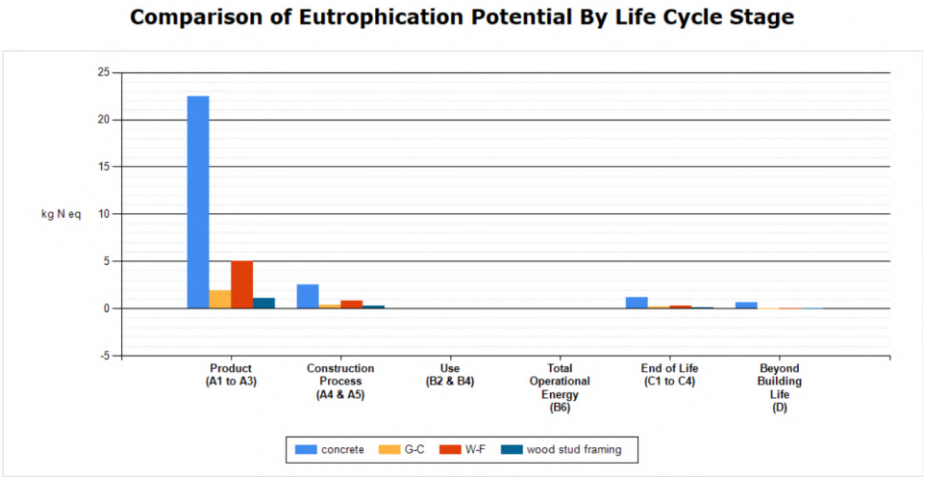


Diagram A. 75: Comparison of Fossil fuel consumption by life cycle stage.

The project with wood stud construction has the lowest potential for eutrophication, as the pie chart illustrates (Diagram A.26).

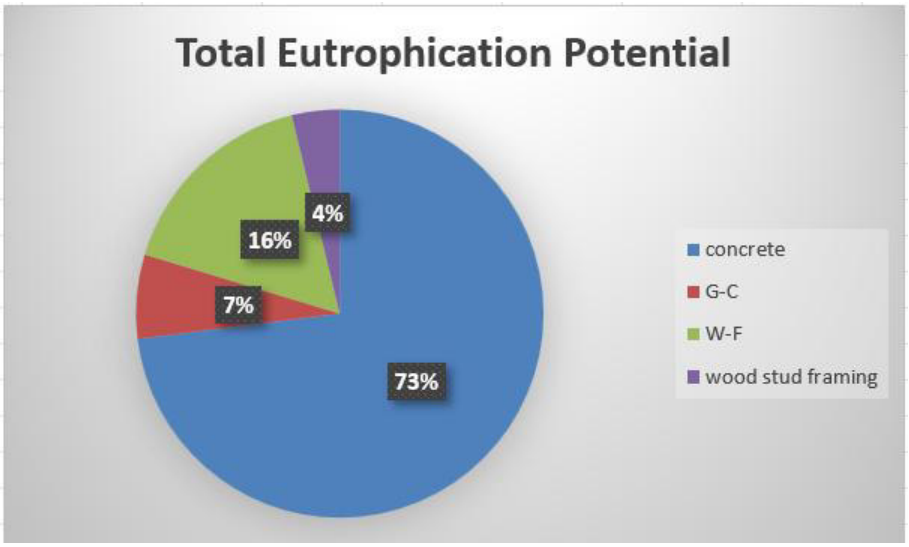


Diagram A. 78: Total Eutrophication Potential

- **Interpretation:**

The worth option:

In comparison other systems Glulam columns & beams and light-frame wood floor trusses supporting ¾" plywood floors need least energy usage in life cycle, because Light-frame construction is a lightweight building technique that reduces material usage and enhances energy efficiency in installation and transportation. Modern manufacturing technologies enable precise and controlled production of glulam and light-frame construction systems, reducing waste and energy consumption. Wood-based construction systems like light-frame and glulam offer adaptability, simplifying structure modifications, extending building lifespan, and reducing demand for new ones. And in general, less energy is needed to produce glulam and light-frame buildings than to manufacture materials like steel or concrete. It can use less energy to create glue-laminated timber by gluing smaller wood pieces together than it does to produce typical solid wood beams or by employing materials like steel and concrete.

Compared to other construction methods, wood stud framing walls may have a lower risk for smog for the following reasons:

- When compared to other materials, wood frequently has a lower embodied energy.
- Renewable Resource: Wood is a resource that may be used to create structures in a way that is sustainable for the environment if it is harvested responsibly. Replanting trees contributes to the sustainability of the cycle.
- Carbon dioxide may be absorbed by wood. As they develop, trees take up CO_2, which is then stored in the wood. Carbon emissions may be mitigated in part by using wood in buildings.
- Compared to certain other building materials, such as steel or concrete, the manufacture of wood products often uses less energy. Emissions may decrease because of this reduced energy use.
- Woods could eventually break down organically at the conclusion of its life cycle without harming the environment in the long run.

Certain characteristics of wood stud framing walls with light-frame wood floor trusses may contribute to a decreased eutrophication potential when compared to other construction systems because of Low Chemical Inputs. Compared to some other

building materials, wood products often require fewer chemical inputs throughout the manufacturing process. Wood building solutions can aid in lowering the amount of stormwater runoff and related nutrient pollution, particularly when paired with suitable site management techniques. Because wood absorbs water, it helps reduce soil erosion and nutrient runoff into surrounding water bodies when used in building sites that are maintained well.

The Worth Option:
Among all systems Concrete columns supporting a 2-way concrete slab floor is the worst in terms all smog potential, fossil fuel, and eutrophication. Carbon dioxide (CO_2) emissions are mostly caused by the manufacturing of cement. Carbon dioxide is released during the chemical conversion of limestone to clinker, which exacerbates climate change and the greenhouse gas effect. The carbon footprint is further increased by the transportation of both completed concrete products and raw materials. The extraction of raw materials for concrete, such as limestone, can disturb ecosystems and deplete resources. The raw ingredients are treated in cement kilns, which run at extremely high temperatures, frequently surpassing 1,400 degrees Celsius. A significant amount of energy is required to achieve high temperatures, which is often derived from fossil fuels such as coal, natural gas, or oil. Transportation of raw materials to cement factories and completed concrete to building sites consumes a lot of energy, especially if the raw materials or final products have to travel great distances. While the energy required for mixing and cutting concrete on a building site is less than that necessary for cement manufacture, it nevertheless contributes to the overall energy consumption of the concrete system.

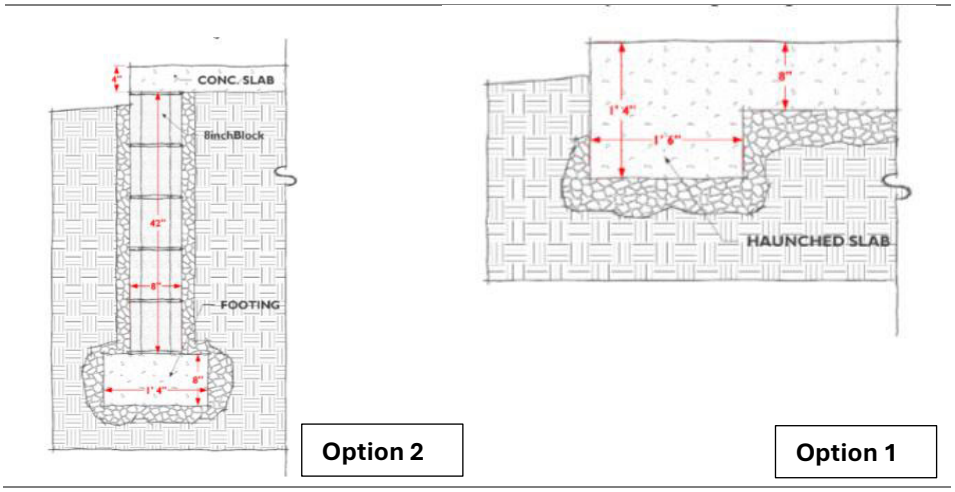
Explanation about being valid or not valid study:
It is noteworthy that a construction system's environmental influence is intricate and multidimensional. A building's overall sustainability is influenced by a variety of elements, including the materials used during construction, transportation, energy efficiency, and end-of-life concerns. A life cycle assessment (LCA) that considers the whole life cycle of the building materials and construction system would be required to make a thorough assessment of the potential for eutrophication. This covers the procurement of raw materials, production procedures, conveyance, building, utilization, and final disposal or recycling. Any construction system's environmental impact must be kept to a minimum by using sustainable building techniques, ethical procurement, and effective site management. Therefore, more information must be added to the architectural models to produce more reliable findings. So to answer this question: Do you think this is a valid study? In my opinion in general, all the stages of the construction of a building are dependent on each other and influence each other. In general, it can be said that the system is better, or which one is worth, but it is not possible to make a definite decision about how much each system has influence in the environmental impact categories. And modeling should be done with finer details.

Functional Unit:
The functionality could be volume or mass of construction materials, or per area of the building.

- **Assignment's 1 Answer: Section 2**

- **Project description:**

life cycle assessment two equally effective foundation options for the proposed 10,000 square foot, single-story structure, with a footprint below features:
One option is a 4-inch-thick slab on grade, with a ±42-inch high 8-inch concrete-block perimeter foundation wall supported on a continuous 8-inch thick by 16-inch-wide strip-footing. The other option is an 8-inch-thick concrete slab on grade with a simple, turn-down (hunched) slab edge as the footing. The turn-down edge measures 16-inches deep (8-inch slab plus 8 additional inches below the slab) and is 18-inches wide. See sketches below for details.



The functional unit might be defined by the area of land impacted by construction operations.

Since cement manufacture contributes significantly to carbon emissions in concrete, Embodied carbon is one of critical LCAI at this stage. Concrete manufacturing uses a lot of water, both directly in the mixing process and indirectly in the extraction and transportation of raw ingredients, therefore another critical LCAI at this stage will be water consumption and water footprint. High energy use over the whole life cycle, including manufacturing, transportation of materials for foundation would be another critical life cycle assessment impact.

- **Analysis**

Option 1:

Table A. 30: Billing of Materials (Option 1)

Bill of Materials Report

Project: Rydel Hall

Material	Unit	Total Quantity	Columns & Beams	Floors	Foundations	Roofs	Walls	Project Extra Materials	Mass Value	Mass Unit
Concrete Benchmark USA 3000 psi	yd3	429.6298	0.0000	0.0000	429.6298	0.0000	0.0000	0.0000	830.3883	Tons (short)
Welded Wire Mesh / Ladder Wire	Tons (short)	1.5591	0.0000	0.0000	1.5591	0.0000	0.0000	0.0000	1.5591	Tons (short)

Table A. 31: Condensed LCA measure table by life Cycle stages

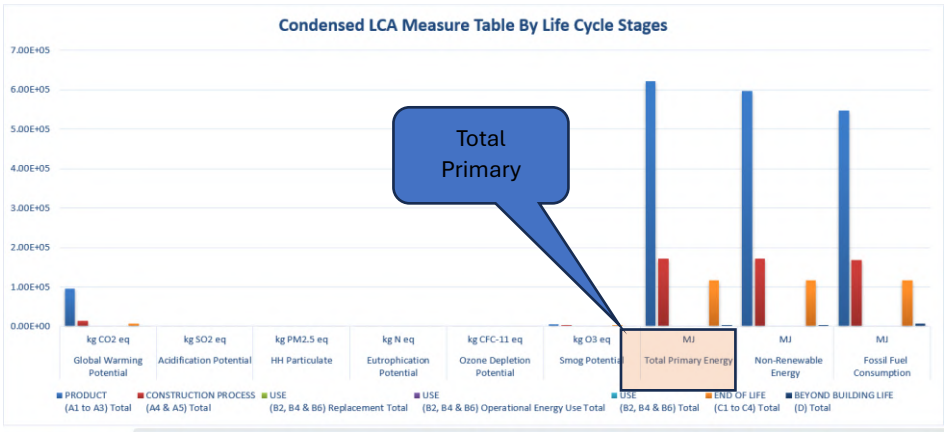
Condensed LCA Measure Table By Life Cycle Stages

Project: Ryder Hall Option 1

		PRODUCT (A1 to A3)	CONSTRUCTION PROCESS (A4 & A5)	USE (B2, B4 & B6)			END OF LIFE (C1 to C4)	BEYOND BUILDING LIFE (D)	TOTAL
LCA Measures	Unit	Total	Total	Replacement Total	Operational Energy Use Total	Total	Total	Total	A to C
Global Warming Potential	kg CO2 eq	9.62E+04	1.44E+04	0.00E+00	0.00E+00	0.00E+00	7.88E+03	7.00E+02	1.18E+0
Acidification Potential	kg SO2 eq	2.84E+02	1.05E+02	0.00E+00	0.00E+00	0.00E+00	1.02E+02	1.60E+00	4.91E+0
HH Particulate	kg PM2.5 eq	7.05E+01	6.26E+00	0.00E+00	0.00E+00	0.00E+00	3.29E+00	7.04E-01	8.01E+0
Eutrophication Potential	kg N eq	1.07E+02	1.07E+01	0.00E+00	0.00E+00	0.00E+00	6.34E+00	8.25E-02	1.24E+0
Ozone Depletion Potential	kg CFC-11 eq	2.29E-03	1.14E-04	0.00E+00	0.00E+00	0.00E+00	3.24E-07	0.00E+00	2.40E-0
Smog Potential	kg O3 eq	5.62E+03	3.16E+03	0.00E+00	0.00E+00	0.00E+00	3.34E+03	1.62E+01	1.21E+0
Total Primary Energy	MJ	6.22E+05	1.72E+05	0.00E+00	0.00E+00	0.00E+00	1.17E+05	3.21E+03	9.11E+0
Non-Renewable Energy	MJ	5.97E+05	1.71E+05	0.00E+00	0.00E+00	0.00E+00	1.17E+05	3.21E+03	8.85E+0
Fossil Fuel Consumption	MJ	5.48E+05	1.69E+05	0.00E+00	0.00E+00	0.00E+00	1.16E+05	6.45E+03	8.33E+0

The bar chart shows products are the most important part of life cycle stages since they play a critical role in all environmental impact categories. But among all categories total primary energy is most critical in all life cycle stages.

Diagram A. 28: Condensed LCA Measure Table by Life Cycle Stages



Option 2:

Table A. 32: Bill Materials Report

Bill of Materials Report

Project: Ryder Hall option 2

Units: SI / Imperial

Material	Unit	Total Quantity	Columns & Beams	Floors	Foundations	Roofs	Walls	Project Extra Materials	Mass Value	Mass Unit
8" Normal Weight Concrete Block	Blocks	21,919.0787	0.0000	0.0000	0.0000	0.0000	21,919.0787	0.0000	428.3859	Tons (short)
Concrete Benchmark USA 3000 psi	yd3	302.9071	0.0000	0.0000	302.9071	0.0000	0.0000	0.0000	585.4586	Tons (short)
Grout-Coarse	yd3	59.7158	0.0000	0.0000	0.0000	0.0000	59.7158	0.0000	107.4987	Tons (short)
Mortar	yd3	48.6876	0.0000	0.0000	0.0000	0.0000	48.6876	0.0000	77.4699	Tons (short)
Rebar, Rod, Light Sections	Tons (short)	15.8735	0.0000	0.0000	12.2247	0.0000	3.6489	0.0000	15.8735	Tons (short)
Welded Wire Mesh / Ladder Wire	Tons (short)	0.9253	0.0000	0.0000	0.9253	0.0000	0.0000	0.0000	0.9253	Tons (short)

Table A. 33: Condensed LCA measure table by life

	PRODUCT (A1 to A3)	CONSTRUCTION PROCESS (A4 & A5)	USE (B2, B4 & B6)			END OF LIFE (C1 to C4)	BEYOND BUILDING LIFE (D)	TOTAL EFFECTS	
LCA Measures	Total	Total	Replacement Total	Energy Use Total	Total	Total	Total	A to C	A to D
Global Warming Potential	1.49E+05	1.90E+04	0.00E+00	0.00E+00	0.00E+00	1.14E+04	7.40E+03	1.79E+05	1.86E+05
Acidification Potential	6.02E+02	1.33E+02	0.00E+00	0.00E+00	0.00E+00	1.45E+02	1.70E+01	8.81E+02	8.97E+02
HH Particulate	1.56E+02	1.07E+01	0.00E+00	0.00E+00	0.00E+00	5.73E+00	7.44E+00	1.73E+02	1.80E+02
Eutrophication Potential	1.14E+02	1.32E+01	0.00E+00	0.00E+00	0.00E+00	9.04E+00	8.72E-01	1.36E+02	1.37E+02
Ozone Depletion Potential	2.69E-03	1.63E-04	0.00E+00	0.00E+00	0.00E+00	4.67E-07	0.00E+00	2.85E-03	2.85E-03
Smog Potential	8.57E+03	3.67E+03	0.00E+00	0.00E+00	0.00E+00	4.76E+03	1.72E+02	1.70E+04	1.72E+04
Total Primary Energy	1.39E+06	2.30E+05	0.00E+00	0.00E+00	0.00E+00	1.68E+05	3.40E+04	1.79E+06	1.83E+06
Non-Renewable Energy	1.35E+06	2.27E+05	0.00E+00	0.00E+00	0.00E+00	1.68E+05	3.40E+04	1.75E+06	1.78E+06
Fossil Fuel Consumption	1.16E+06	2.21E+05	0.00E+00	0.00E+00	0.00E+00	1.68E+05	6.81E+04	1.55E+06	1.62E+06

The bar chart shows products are the most important part of life cycle stages since they play a critical role in all environmental impact categories. But among all categories total primary energy is most critical in all life cycle stages.

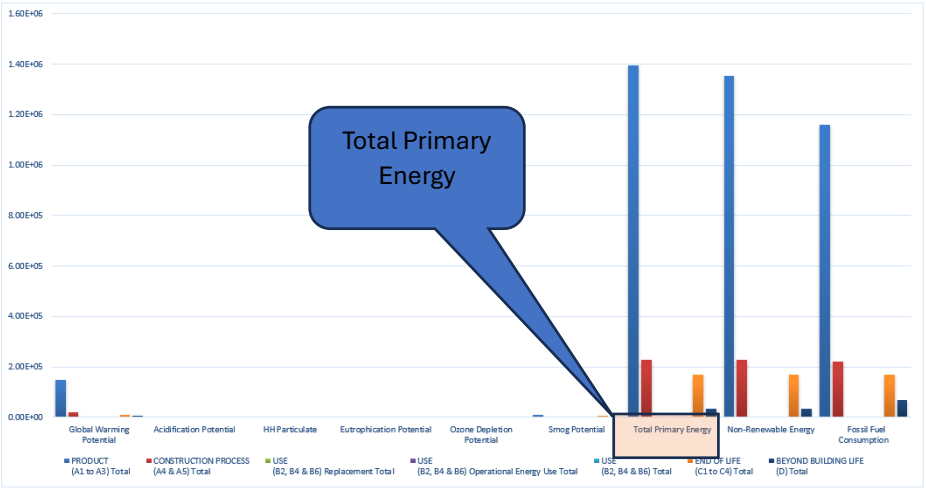


Diagram A. 29: Condensed LCA Measure Table by Life Cycle Stages

- **Comparison of different options:**

The result shows that Global warming is most critical in option 2 (the option with concrete-perimeter foundation wall supported).
Among all life cycle stages products process (A1 to A3) will have the most critical role in global warming in both 2 options.

Project Name	Unit	Product (A1 to A3)	Construction Process (A4 & A5)	Use (B2 & B4)	Total Operational Energy (B6)	End of Life (C1 to C4)	Beyond Building Life (D)	Total
Ryder Hall Option 1	kg CO2 eq	9.62E+04	1.44E+04	0.00E+00	0.00E+00	7.88E+03	7.00E+02	**1.19E+05**
Ryder Hall option 2	kg CO2 eq	1.49E+05	1.90E+04	0.00E+00	0.00E+00	1.14E+04	7.40E+03	**1.86E+05**
Total	**kg CO2 eq**	**2.45E+05**	**3.34E+04**	**0.00E+00**	**0.00E+00**	**1.92E+04**	**8.10E+03**	**3.05E+05**

Table A. 34: Comparison of Global Warming Potential By Life cycle stage

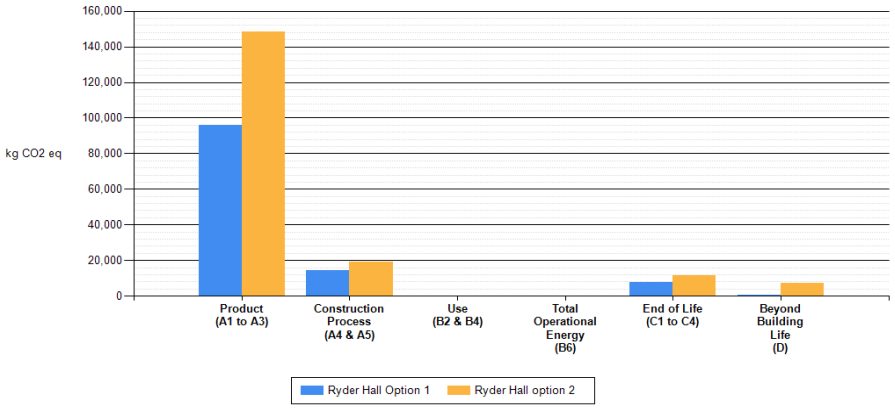


Diagram A. 30: Comparison of Global Warming Potential By Life Cycle Stage

- **Analysis after adding Fly ash**

Table A. 35: Billing materials Report (option 1)

Bill of Materials Report

Project: Ryder Hall option 2

Units: SI / Imperial

Material	Unit	Total Quantity	Columns & Beams	Floors	Foundations	Roofs	Walls	Project Extra Materials	Mass Value	Mass Unit
8" Normal Weight Concrete Block	Blocks	21,919.0787	0.0000	0.0000	0.0000	0.0000	21,919.0787	0.0000	428.3859	Tons (short)
Concrete Benchmark USA 3000 psi	yd3	302.9071	0.0000	0.0000	302.9071	0.0000	0.0000	0.0000	585.4586	Tons (short)
Fly Ash	Tons (short)	35.0000	0.0000	0.0000	35.0000	0.0000	0.0000	0.0000	35.0000	Tons (short)
Grout-Coarse	yd3	59.7158	0.0000	0.0000	0.0000	0.0000	59.7158	0.0000	107.4987	Tons (short)
Mortar	yd3	48.6876	0.0000	0.0000	0.0000	0.0000	48.6876	0.0000	77.4699	Tons (short)
Rebar, Rod, Light Sections	Tons (short)	15.8735	0.0000	0.0000	12.2247	0.0000	3.6489	0.0000	15.8735	Tons (short)
Welded Wire Mesh / Ladder Wire	Tons (short)	0.9253	0.0000	0.0000	0.9253	0.0000	0.0000	0.0000	0.9253	Tons (short)

Table A. 36: Billing materials Report (option 2)

Project Name	Unit	Product (A1 to A3)	Construction Process (A4 & A5)	Use (B2 & B4)	Total Operational Energy (B6)	End of Life (C1 to C4)	Beyond Building Life (D)	Total
Ryder Hall	kg CO2 eq	9.66E+04	1.44E+04	0.00E+00	0.00E+00	8.13E+03	7.00E+02	**1.20E+05**
Ryder Hall option 2	kg CO2 eq	1.49E+05	1.90E+04	0.00E+00	0.00E+00	1.16E+04	7.40E+03	**1.87E+05**
Total	**kg CO2 eq**	**2.46E+05**	**3.34E+04**	**0.00E+00**	**0.00E+00**	**1.98E+04**	**8.10E+03**	**3.07E+05**

Diagram A. 31: Comparison global warming

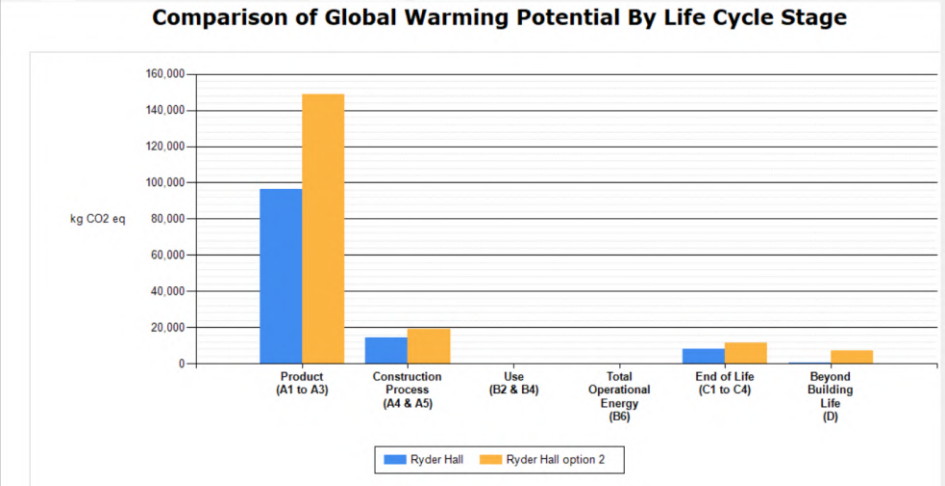
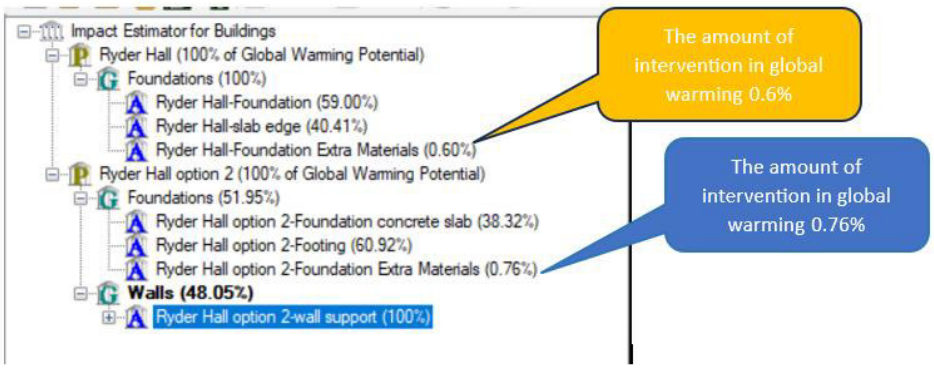


Figure A. 58: Comparison Global warming



The result shows the decrease global warming impact caused by this project amount 1 percentage in both options after adding fly ash.

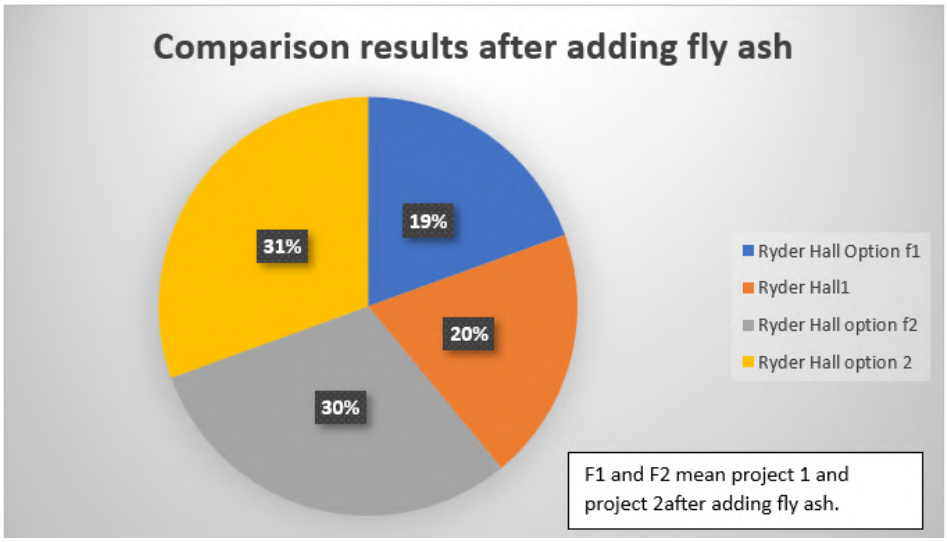


Diagram A. 32: Comparison Result after adding fly ash

A.3.2.4.2 Assignment 2 Title: ENERGY AND SIMULATION

In this assignment, we contined our project of a sustainable retrofit of a campus building, in this case, Ryder Hall. We were going to use a simple building performance simulation to consider the energy performance of the existing building, and as a baseline against which to test possible alternative design options for renovation.

We used COMFEN to model a representative south-facing classroom space in Ryder Hall. The existing space is described below; we had to simulate this "baseline" and then possible variations to reduce energy use. Then we had to write our answers directly question sheet, and then submit that assignment online.
COMFEN was available free from https://windows.lbl.gov/comfen-downloads and was installed in the College of Engineering Computer Labs.

Baseline Building and Rotations:

Once you have the model built, simulate it, and write the baseline energy use intensity here: Baseline.

Building EUI----------tu/ft²•year

Now make three additional scenarios, and change the orientation of the space in each, one so you can simulate the classroom on the east, north and west facades of the building. Compare those options and list those results below.

East Orientation EUI: ----------kBtu/ft²•year Percent of Baseline: ----------%

North Orientation EUI: ----------kBtu/ft²•year Percent of Baseline: ----------%

West Orientation EUI: ----------kBtu/ft²•year Percent of Baseline: ----------%

Optimization:

Finally, we had to create a new scenario (or scenarios) and begin testing ways to reduce the

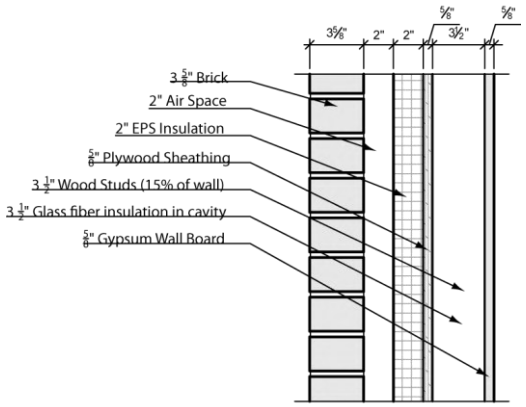
energy consumption of the baseline, south-facing space. Our goal was to get to the lowest EUI possible. We may wish to test one change at a time (e.g. improve wall thermal resistance, improve glazing thermal resistance) to see the relative impact. You may also need to evaluate combinations of changes (e.g. clearer glass increases the heat gain, but simultaneously reduces lighting energy if you have daylight dimming). Some interactions Could become quite complex, for example those involving exterior shades. We had to Write the energy use for our optimized, lowest-energy design on the line below, and itemize the differences between our optimal design and the baseline (in notes and/or by marking up the drawings).

Optimized South EUI:----------kBtu/ft²•year Percent of Baseline:---------- %

Measures taken to optimize:

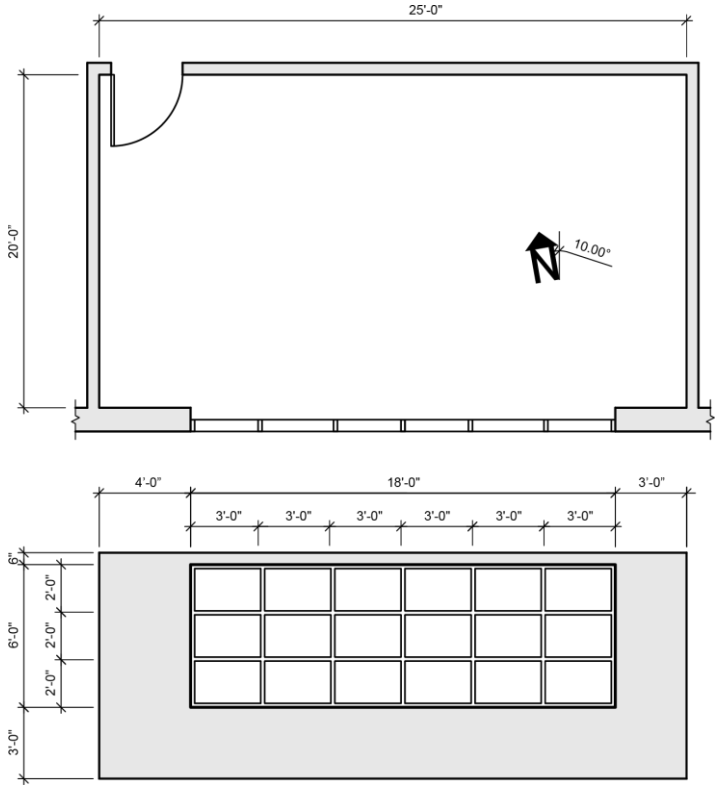
Baseline Building Design

The project was an classroom space located in Boston, on the southern side of a building that is oriented ten degreesfrom true north as shown in the plans below. The fenestration has aluminum frames with a thermal break, and a single layer of 6mm clear glass in all panes. The plan, elevation and opaque wall assembly are drawn below.
NB: This was not really the Ryder wall assembly, and we needed to build a custom assembly to match the properties below.



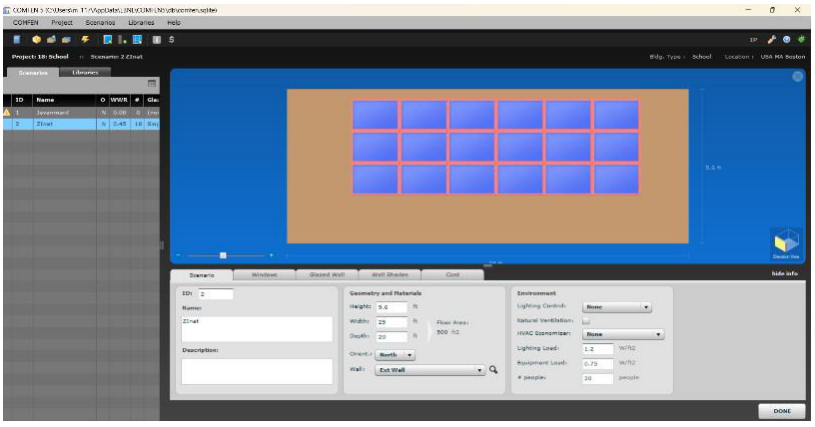
The lighting power density is 1.2 W/ft². There willon average be 20 occupants and 0.75 W/ft² of equipment. There is no natural ventilation, economizer, or daylight control in the **base** building, but you can consider adding them as partof your proposed renovation.

In modifying the design to achieve optimal energy performance, we could change any parameter except the basic dimensions of the space(height, width, and room depth) and we must still provide fenestration for view. we could Use images, words, or drawings to describe the system you are using for your minimum energy consumption design.



➢ Assignment's 2 Answer: ENEGY AND SIMULATION

Modeling South elevation as Baseline:



First Step:
Compare Energy usage Between different orientations:

Table A. 37: Compare Energy usage Between different orientations

ID	Scenario	EUI	Percentage of Baseline
1	South	75.6	-
2	Est	84.11	111.26
3	North	87.09	115.20
4	West	88.83	117.5



Diagram A. 33: Compare Energy usage Between different orientations

Step 2:

Comparison Baseline and a New Scenario:

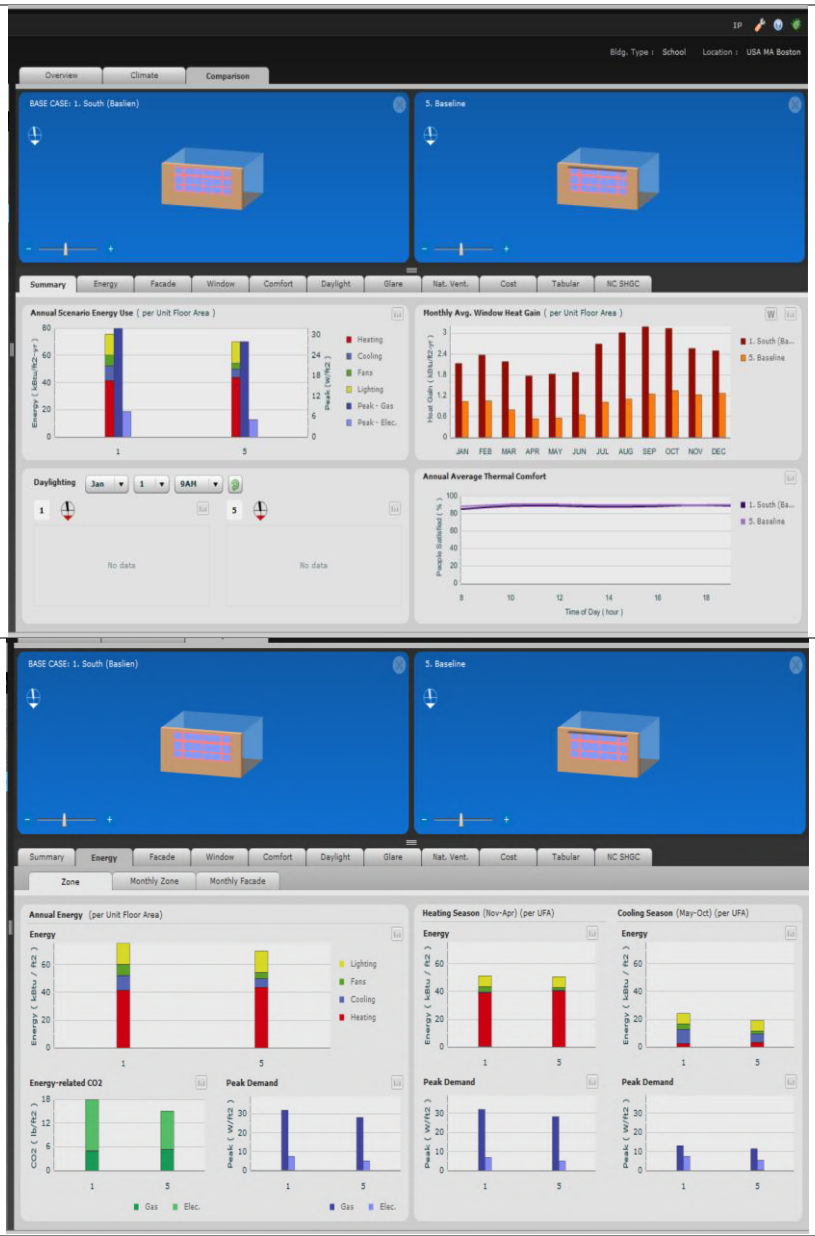


Diagram A. 82: Comparison Baseline and a New Scenario

ID	Scenario	EUI	Percentage of Baseline
1	Baseline	75.60	-
5	Scenario	69.88	92.43

Table A. 38: Comparison Baseline and a New Scenario

Suggestion:

- Changing the Glazed Wall assembly: Double Bronze (Air)
- Wall shading: Depth 2, with 18

A.3.2.4.3 Assignment 3 Title: The Life Cycle Cost

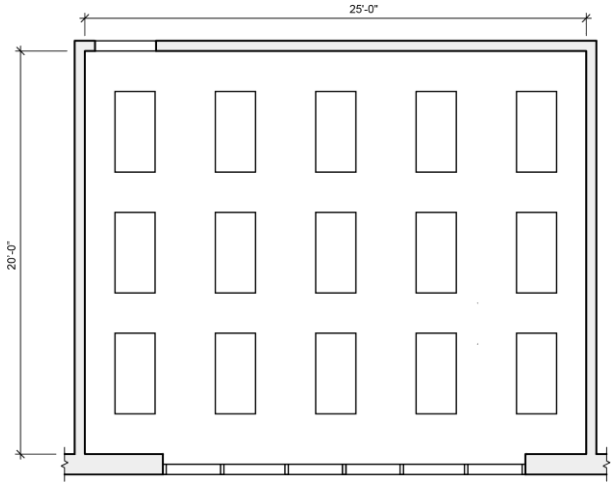
Overview of this Section:

In this module, we transitioned to consider the business, management, and financial impacts (costs and benefits) of environmental choices. While this was obviously not an economics course, some basic familiarity with the methods and terminology could serve us well should we ever want to implement sustainability in the built environment. we worked from the macro-scale of corporate sustainability accounting—including systems like Triple Bottom Line accounting—and from the micro-scale of the economic calculations used to inform individual design decisions.

Explanation of Assignments:

For this assignment, we needed to refer to the I. L. E. Committee. Recommended Practice for the Economic Analysis of Lighting. Illuminating Engineering Society of North America, 1996. (NB: There are a few unit-conversion errors in the original document, a corrected version is posted on the course website). It was necessary we Note also that the values below were estimates for learning purposes, and so did not necessarily reflect actual numbers for the University!

As part of the ongoing renovation design for Ryder Hall, we have been asked to evaluate the economic performance of several lighting design options for the classroom space we studied in the simulation assignment. Recall that it measures 25 feet by 20 feet (500 ft³ total). Northeastern expects to use the building for 20 years before the next renovation (ha!) and makes investment decisions using a discount rate of 10%. The building is in Boston (obviously) and normally operates 10 hours/day, 5 days/week, 52 weeks/year (including summer classes). Although Northeastern is tax exempt, it will voluntarily pay 6.25% sales tax on the first cost of the building materials and consider income taxes in financial analysis in case Congress enacts a proposed tax on educational institutions with endowments. Per current IRS guidelines, the lighting system will depreciate over 39 years, and the University will assume a 38% annual income tax rate. The Payment in Lieu of Taxes (PILOT) rate negotiated with Boston is 5%, and the insurance rate is 1%.



The lighting designer had prepared two alternatives that both provided equal light levels and quality. The first aligned with this client's existing standard light fixture, and uses fifteen 2'x4' fluorescent fixtures, each with two, T-12 lamps at 40 watts per lamp, demanding. 2.4 W/sf of lighting. Each fixture costs $134 to install. The second alternative also uses fifteen 2'x4' fluorescent fixtures, however, in this scheme, each fixture uses two T-8 HO (high output) lamps at 32 watts per lamp, for 1.92 W/sf of lighting at a first cost of $148 per fixture.
The lamps in both fixtures had an expected life of 30,000 hours, they cost $15 to replace, and the owner operates on a spot-replacement strategy (hence standard lamps). Each fixture had one ballast, which was expected to last 100,000 hours, and cost $100 to replace. At the end of the fixture's life, it should cost $10 to remove them and dispose of them safely. Both fixtures cost $12 to clean, and the owner expects to clean them once each year. We had to consult with the mechanical engineer and determine that the building would need cooling 1,600 hours per year and require heating for1,000 hours. The mechanical engineer had helpfully provided the following cos:

First Cost for Air Conditioning	**$3,000/ton of cooling**	**Annual maintenance for Air Conditioning:**	**$150/ton of cooling**
First cost for Heating:	**$20/MMBtuh**	**Annual maintenance for Heating**	**$2/MMBtu heating**

Although we had to assume that presently connected to the central steam plant, the HVAC design following the renovation consists of Roof Top Units (RTUs), using Direct Expansion (DX) cooling with an efficiency of 1.2 kW/ton of cooling, and a gas-fired furnace with 60% efficiency for heating. (NB: This would be an unfortunate downgrade of efficiency!)

Electricity for both lighting and cooling costs 15.7 cents/kWh. Gas for heating costs $11.68/thousand cubic feet. There were no utility incentives available for this project. Use the method outlined in IESNA RP-31-96 to compare the economic performance of these alternatives.

	Annualized Cost Basis	**Present Value Basis**
1.System One T-12:	$ 1418.44	$ 12084.92
2.System Two T-8 HO:	$ 1302.2	$ 11035.19

Design Alternatives
Having witnessed first-hand the brilliance of our other sustainability work, and the depth of insight in our economic analysis so far, we had to assume that the owner wants to consider a range of other possible design options, including choices to improve environmental performance. we had to Calculate the total annualized costs for the following alternatives, we excepted for parameters that change in these alternatives, assumed all other aspects are identical to System One above).
NB: we had to (if you have not already) develop some form of spreadsheet to make these calculations faster.

3.The lighting designer proposes a new, highly energy-efficient arrangement that achieves the same light levels using only 10 very-high performance 2'x4' fixtures, each

containing two T-5 HO Lamps (at 28 W/lamp) and costing $185/fixture (all other characteristics are the same as above).

- Total Annualized Costs: **900.78 $**

4.Knowing that LED technology is rapidly advancing in efficiency and quality, you contact an LED vendor who suggests a design that requires 20, 2'x2' LED fixtures to achieve adequate illumination. Each fixture contains only one lamp, rated at a mere 29 watts, and it is expected to last 120,000 hours before replacement. The driver (similar to a ballast) will last 300,000 hours. This performance comes at a price, however, each fixture costs $385, and replacing the lamp costs $160, while a new driver costs $200.

- Total Annualized Costs: **2092.92 $**

5.The project architect, based on a presentation at ABX (http://www.abexpo.com/), suggests a newly released LED product that was on display on the exhibit floor. The design would require only fifteen 1'x4' strip fixtures, each with a single, 55 watt LED lamp. Each fixture costs $450. The lamp lasts 60,000 hours, and costs $160 to replace; the driver lasts 300,000 hours and costs $150 to replace.

- Total Annualized Costs: **2056.22 $**

comparing among these design alternatives is the "conventional" application of economic analysis, however you can also compare the effects of changing to the project parameters (e.g. discount rate, lifespan, utility rates, HVAC systems) while keeping the design constant. The IESNA RP-31-96 describes this kind of sensitivity analysis as a way to validate the results by identifying which parameters have a large influence on the result, for example, minor changes to the discount rate may have a far greater effect than the differences between schemes. This is also useful information to understand the project more deeply, and to estimate the risk of an investment into the uncertain future. Experiment with various project parameter values and briefly describe any interesting observations. For example what if Northeastern really is tax-exempt? What if the PILOT rate negotiated with Boston increases, or decreases? Does this seem like a good tool? What are the limitations? How might you address them?

❖ Assimnets'2 Answer: Calculation Process of life cycle cost

To compare the economic performance of the lighting design alternatives using the method outlined in IESNA RP-31-96, we will calculate the life cycle costs for each alternative. The life cycle cost includes the initial cost, operating costs, maintenance costs, disposal costs, and any applicable taxes or incentives over the expected life of the system.

General project features:

- Discount Rate: 10%
- Operational Hours: 10 hours/day, 5 days/week, 52 weeks/year
- Sales Tax Rate: 6.25%
- Depreciation Period: 39 years
- Income Tax Rate: 38%
- PILOT Rate: 5%
- Insurance Rate: 1%
- Expected Life: 20 years

- Cooling Hours: 1,600 hours/year
- Heating Hours: 1,000 hours/year

Assumptions:

- **Discount Rate:** 10%
- **Operating Hours:** 2,600 hours/year for lighting, 1,600 hours/year for cooling, 1,000 hours/year for heating
- **Electricity Cost:** $0.157/kWh
- **Gas Cost:** $11.68/thousand cubic feet
- **Depreciation Period:** 20 years (building use)
- **Sales Tax Rate:** 6.25%
- **Income Tax Rate:** 38%
- **PILOT Rate:** 5%
- **Insurance Rate: 1%**

There are two lighting alternatives that have been designed to provide equal light levels and quality in each space. I broke down the key details:

First Alternative: (T-12 Lamps)	**Second Alternative:** (T-8 Lamps)
▪ **Light Fixture Type:** 2'x4' fluorescent fixtures ▪ **Lamp Type:** T-12 lamps ▪ **Lamp Wattage:** 40 watts per lamp ▪ **Power Demand:** 2.4 watts per square foot (W/sf) of lighting ▪ **Number of Fixtures:** 15 fixtures ▪ **Fixture Cost:** $134 per fixture (including installation) ▪ **Expected Lamp Life:** 30,000 hours ▪ **Lamp Replacement Cost:** $15 per lamp ▪ **Expected Ballast Life:** 100,000 hours ▪ **Ballast Replacement Cost:** $100 per ballast ▪ **Disposal Cost:** $10 per fixture ▪ **Cleaning Cost:** $12 per fixture per year	▪ **Light Fixture Type:** 2'x4' fluorescent fixtures ▪ **Lamp Type:** T-8 HO (high output) lamps ▪ **Lamp Wattage:** 32 watts per lamp ▪ **Power Demand:** 1.92 watts per square foot (W/sf) of lighting ▪ **Number of Fixtures:** 15 fixtures ▪ **Fixture Cost:** $148 per fixture (including installation) ▪ **Expected Lamp Life:** 30,000 hours ▪ **Lamp Replacement Cost:** $15 per lamp ▪ **Expected Ballast Life:** 100,000 hours ▪ **Ballast Replacement Cost:** $100 per ballast ▪ **Disposal Cost:** $10 per fixture ▪ **Cleaning Cost:** $12 per fixture per year

Table A. 39: The features of different Alternative

	Bulbs	First cost	Install	Power	install klw	Hours	energy Cost	Annual energy cost for lighting
first alternative	15	134	2010	80	1.2	2600	0.157	489.84
second Alternative	15	148	2220	64	0.96	2600	0.157	391.872
System3	10	185	1850	64	0.64	2600	0.157	261.248
system4 LED	20	385	7700	29	0.58	2600	0.157	236.756
System 5	15	450	6750	55	0.825	2600	0.157	336.765

Calculation of Lighting system:

	Initial Cost	T-12 Lighting System (First Alternative):	T-8 Lighting System (Second Alternative):	system3(T-5HO)	System4(LED)	system5
A1	System , Light	2010	2220	1850	7700	6750
A2	Total kw lighting	1.2	0.96	0.64	0.58	0.825
A3	tons of air conditioning	0.341	0.2728	0.181866667	0.164816667	0.2344375
A4	first cost of AC	1023	818.4	545.6	494.45	703.3125
A5	reduction in first cost of heat equipment	-0.08184	-0.065472	-0.043648	-0.039556	-0.056265
A6	Utility incentives	0	0	0	0	0
A7	other first costs	0	0	0	0	0
A8	Subtotal mechanical and electrical installed cost	3032.91816	3038.334528	2395.556352	8194.410444	7453.256235
A9	initial taxes	189.557385	189.895908	149.722272	512.1506528	465.8285147
A10	**Total cost**	**3222.475545**	**3228.230436**	**2545.278624**	**8706.561097**	**7919.08475**
A11	Installed cost per square foot	-	-	-	-	-
A12	Watts of lighting per square foot	-	-	-	-	-
A13	salvage value at end of economic life	10	10	10	10	10

Table A. 40: Calculating of initial cost

Annual Power and maintenance Costs		T-12 Lighting System (First Alternative):	T-8 Lighting System (Second Alternative):	system3(T-5HO)	System4(LED)	system5
B1	Lighting Utility cost	489.84	391.872	261.248	236.756	336.765
B2	Air conditioning=	102.79104	82.232832	54.821888	49.682336	70.66884
B3	Air conditioning maintenance	51.15	40.92	27.28	24.7225	35.165625
B4	Reduction in heating cost	-17.47	-13.98	-8.15	-8.45	-12.01
B5	Reduced Heating maintenance	0.008184	0.0065472	0.0043648	0.0019778	0.00281325
B6	Other Annual cost					
B7	lamp replacement Cost	15	15	15	160	160
B8	Ballast replacement Costs	100	100	100	200	150
B9	Luminaire Cleaning costs	180	180	120	240	180
B10	Annual insurance cost	32.22475545	32.28230436	25.45278624	87.06561097	79.1908475
B11	Annual property tax cost	161.1237773	161.4115218	127.2639312	435.3280548	395.9542375
B12	Income tax effect	31.39847967	31.45455297	24.8001507	84.8331594	77.16031295
B13	**Total annual costs**	**1146.066236**	**1021.199758**	**747.7211209**	**1509.939639**	**1472.897676**

Table A. 41: Calculation the Annual Power and maintenance cost

Final calculations: (i=0.01, n=20)

The final equation to find values for annualized cost basis:

$$TAEC=A13+A10\left[\frac{i(1+i)^n}{(1+i)^n-1}\right]+A13\left[\frac{i}{(1+i)^n-1}\right]$$

Table A. 42: The final equation to find values for annualized cost basis

T-12 Lighting System (First Alternative):	T-8 Lighting System (Second Alternative):	system3(T-5HO)	System4(LED)	system5
1418.44	**1302.2**	**900.78**	**2092.92**	2056.22

calculation present value basis:

$$TP=A10+B13\left[\frac{(1+i)^n-1}{i(1+i)^n}\right]+A13\left[\frac{1}{(1+i)^n}\right]$$

Table A. 43: calculation present value basis

T-12 Lighting System (First Alternative):	T-8 Lighting System (Second Alternative):
12084.92	**11035.19**

Interpretation of the data:

In the current study, an evaluation of annualized cost and present value for lighting systems (T-12 and T-8) was conducted, utilizing specific project parameters for comparison. To enhance the reliability of conclusions, it was imperative to extend the economic analysis through sensitivity analysis in different scenarios. . Key observations from the economic analysis include the significant impact of discount rate variations, emphasizing the need to assess different lifespans and recognize sensitivity to utility rate changes. The choice of HVAC systems is crucial in influencing energy consumption and overall project economics. Considerations regarding tax-exempt status and negotiations of PILOT rates underscore the importance of a nuanced evaluation. Despite providing valuable insights, it is essential to acknowledge the limitations of economic analysis, such as reliance on assumptions and uncertainties in future conditions. Addressing these limitations through sensitivity analyses, probabilistic modeling, and scenario analysis enhances the comprehensiveness and reliability of the economic evaluation, forming a robust foundation for decision-making in complex project scenarios.

In the annualized cost comparison, System 3 (T-5HO) emerges as the most cost-effective option among alternatives, indicating favorable ongoing operational expenses. The T-8 Lighting System closely follows, offering a lower annualized cost, while System 4 (LED) and System 5 demonstrate higher annualized costs, implying potentially elevated operational expenses over the project's expected life. In the present value comparison, the T-12 Lighting System exhibits a higher present value than the T-8 Lighting System, suggesting a potentially higher overall cost when accounting for the time value of money. Despite the T-8 system having a higher annualized cost, its lower present value underscores the importance of considering both metrics for a comprehensive evaluation. The cost vs. energy efficiency trade-off is evident in Systems 4 and 5, where higher annualized costs may be associated with improved energy efficiency or unaccounted benefits. This trade-off necessitates a careful consideration of upfront costs versus potential long-term energy savings. Sensitivity analysis becomes paramount, as variations in discount rates, lifespan, utility

rates, and HVAC systems can significantly impact the economic feasibility of each alternative. Recommendations for further analysis include conducting sensitivity analyses on critical parameters to assess conclusion stability under different scenarios and exploring the impact of potential changes in tax-exempt status, PILOT rates, or other project parameters to provide a more comprehensive perspective. In conclusion, while System 3 appears to be a cost-effective choice, a nuanced examination of parameter sensitivity and long-term benefits, such as energy efficiency, is essential in the decision-making process.

Investigating the sensitivity:
To enhance the "best" system identified in the economic analysis (presumably System 3, T-5HO, with the lowest annualized cost), several strategic adjustments to project parameters can be explored. Firstly, investigating the impact of tax-exempt status, assuming a 0% income tax rate for Northeastern, could potentially elevate the system's economic attractiveness by significantly influencing present value and annualized cost. Additionally, negotiating favorable terms in the Payment in Lieu of Taxes (PILOT) rate with Boston could decrease operational costs (with a lower rate) or increase costs (with a higher rate), emphasizing the importance of favorable agreements with local authorities. Further, adjusting the discount rate can assess sensitivity to changes in the cost of capital, with higher rates favoring projects with earlier returns and lower rates potentially favoring long-term projects. Exploring the effects of varying lifespans on economic indicators can provide insights into overall cost-effectiveness, with longer lifespans potentially improving system performance. Analyzing fluctuations in utility rates, specifically electricity and gas costs, is crucial, given their significant impact on operational costs. Recognizing the limitations of economic analysis, including reliance on assumptions and sensitivity to parameters, warrants addressing uncertainties through probabilistic modeling, scenario analysis, real options analysis for long-lived projects, continuous monitoring, and consultation with experts.

A.3.2.4.4 Assignment 3 Title: IEQ WELLBEING, PRODUCTIVITY

Overview of this module
Over the several weeks, we had amassed considerable knowledge about sustainable buildings. We had considered many scales, from building components and materials to whole buildings, sites, and even regions. We had considered measuring the sustainability of energy, water, and materials. So we had to quickly jump down to the human scale, and consider whether and how of buildings affect health, productivity, and comfort. To test that theory, we had to evaluate our own perceptions of IEQ.

Explanation of assignment
Two of this module's readings traced a conversation in the research literature about the effect (if any) of the LEED rating system on occupant comfort and satisfaction. One of the curious realities about people was that we tended to notice differences but were generally unconscious of the status quo. Similarly, we tended to notice and record dissatisfaction whilst remaining blissfully unaware of comfort. This assignment invited us to become more conscious of our own sensations and satisfaction with the indoor environmental quality of the places we visited.
we had to conduct an IEQ Self Survey over several days, generating a quantitative record of our qualitative personal experiences. This was a so-called Ecological

Momentary Assessment or "right-now" survey, which means it should have relatively few questions (no more than ten) and should focus on your immediate experiences and sensations. At a minimum we had to record the following thermal elements, although you are of course welcome to add other questions:

•Where you are and what time it is.

•Your thermal sensation using a standard, seven-point scale below:

+3 hot, +2 warm, +1 slightly warm, 0 neutral, -1 slightly cool, -2 cool, -3 cold

•our thermal satisfaction (also 7-points but from very satisfied to very dissatisfied)

•Some record of our clothing level and activity level (clo factor and met rate, see https://comfort.cbe.berkeley.edu/ for references and explanation of these terms)

•Some record of "perceived productivity" (this may be easy if we were in class or working, if you are "productively relaxing" we might record how well or poorly the thermal environment was enabling that.)

We had to choose a systematic format for recording that made it easy to take the survey, and easy to analyze the data afterwards. Possible approaches included using a series of paper forms, a spreadsheet, a smartphone app, or an online survey tool like Google Surveys or Survey Monkey. We should also arrange some system that prompted us to take the survey at frequent (possibly regular, possibly random) intervals throughout the study period. Ideally, we had to create at minimum one record every 2-3 hours to amass a good-sized data set.

In conjunction with this survey, we had to use our data logging temperature sensor to record measured data about our thermal environment. We needed not to refer to this during the survey period, simply set it up to log at a regular interval and carry it with us everywhere during the study. we had to be sure to carry the sensor in a way that does not influence the temperature, for example, it is much warmer in our pocket than the ambient air. our maximum logging interval was ten minutes, intervals shorter than a minute rarely add much useful information. At the end of the study, we had to download the data from the logger to analyze the temperature history of our week.

When we were finished with the study period, we had to compile our quantitative and qualitative data and then analyze our results using charts and graphs as required. One obvious analysis was an x-y plot with a point for each time we completed the survey. Plot thermal satisfaction on y as a function of thermal sensation on x. A linear relationship showed if we were we happier in cool, neutral, or warm environments. we may also want to correlate the measured temperature with our thermal sensation and see how "accurate" our internal thermometer was. we might compare your data to the standards such as ASHRAE 55—perhaps using the CBE comfort tool—by plotting the environmental conditions we experienced against the theoretical comfort zone to see how well the standard's prediction of comfort aligned with our experience of satisfaction (or not). These were only some easy examples, but we should use our imagination and curiosity.

Finally, we had to prepare a brief report that gave an overview of our study method, summarizes our findings and analysis of them, and we had to provide a thoughtful conclusion summarizing what (if anything) we learned. we had to seek to assemble a coherent thesis, argument that took advantage of both forms of information us gathered: the survey of sensation/satisfaction coupled with data about temperature to learn something interesting about IEQ, comfort, satisfaction, productivity etc. our report had to total no more than four pages including figures. This should not included

a cover, appendices, or raw data tables. Like any research paper, the report had to present the method, findings, analysis, and conclusions, rather than simply a data-dump of facts. This was an individual assignment, so it should go without saying that all the work, and all the responses should be our own. Hence the self-survey! The report was due as a single PDF via the course webpage.

❖ Assimnets'3 Answer: IEQ, WELLBEING, PRODUCTIVITY

Explanation of Data:
The measure of satisfaction was stratified within a spectrum ranging from -3, indicative of no satisfaction, to 3, denoting complete satisfaction.
The thermal sensation scale, as a standard, is delineated into seven points: +3 denoting hot, +2 signifying warm, +1 indicating slightly warm, 0 representing neutral, -1 suggesting slightly cool, -2 connoting cool, and -3 corresponding to cold. I also took into consideration a productivity assessment scale ranging from -3 to 3.
1- The examination of data pertaining to November 21 was undertaken to assess productivity levels contingent upon subjective satisfaction with ambient temperature. The dataset spans a 24-hour period. A typical day in my routine encompasses a one-hour walk to the university, followed by a day spent in my office. Subsequently, I embark on a one-hour return walk from the university to my residence, engage in culinary activities, dedicate time to study, and engage in brief periods of rest before retiring for the night, culminating in a sleep cycle.

The level of contentment regarding ambient temperature is contingent upon both the extent of attire worn and the nature of the undertaken activities. Preferences fluctuate based on distinct activities, with a proclivity for a cooler environment during certain tasks and a requisite for a warmer setting during others. To illustrate, while stationed in my office during hours when the external air temperature matches the interior ambient temperature (owing to the absence of illumination and heating systems), and engaging in cerebral endeavors, I find a warmer environment necessary for optimal satisfaction (Diagram A.35,A.36).

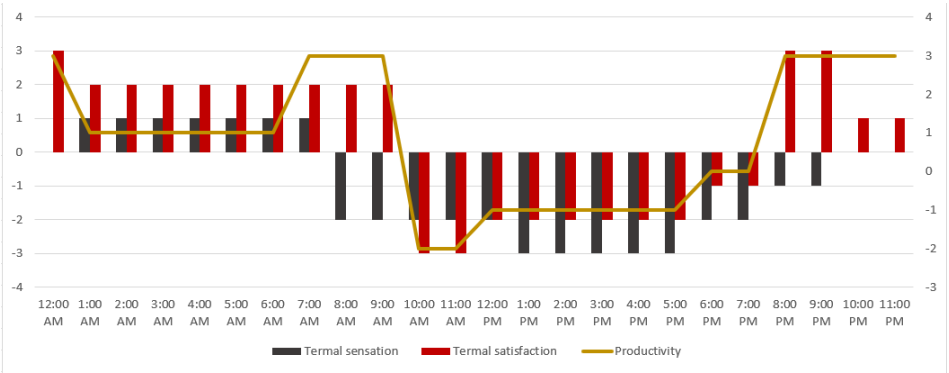


Diagram A. 83: Relation between Thermal Sensation and thermal satisfaction with Productivity

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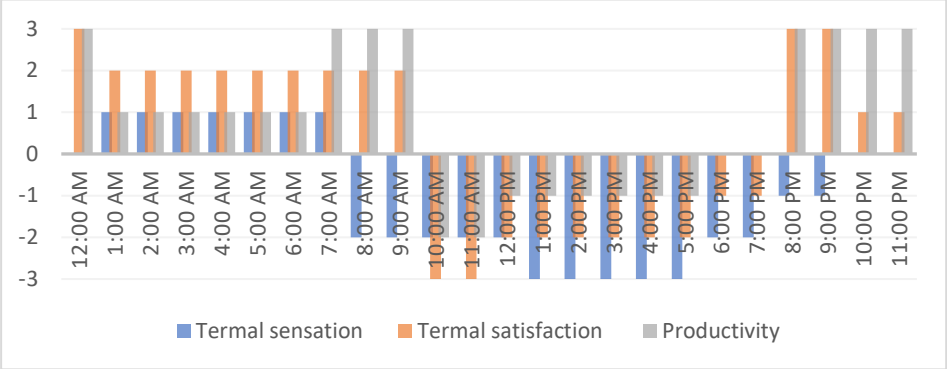


Diagram A. 36: Relation between Thermal Sensation and thermal satisfaction with Productivity.

It has come to my attention that during leisure intervals, characterized by a diminished necessity for intellectual activity, a cooler ambient environment engenders a heightened sense of satisfaction and enhances my concentration. Conversely, when engaging in study-related activities within my office, which inherently involves heightened cognitive demand, exposure to a colder environment is associated with a concomitant decrement in activity efficiency. This divergence in preferences underscores the subjective nature of thermal satisfaction, emphasizing its reliance on individual idiosyncrasies (Diagram A.37).

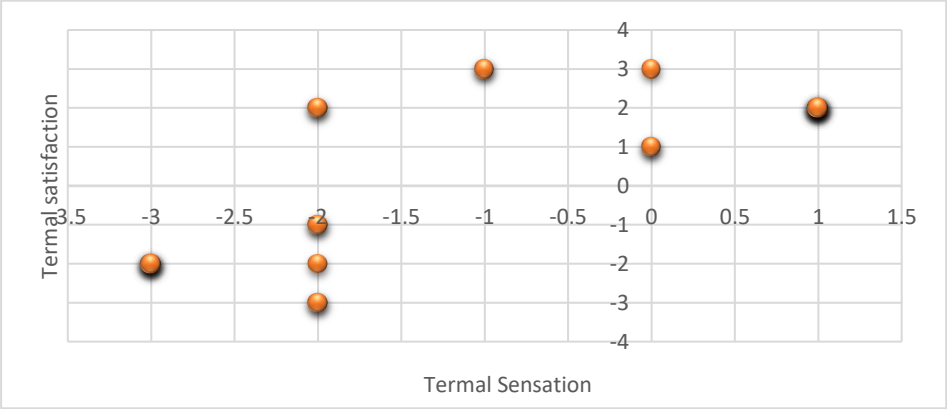


Diagram A. 84: Thermal Sensation and Thermal satisfaction

2- Clothing Level (CLO) CLO is a numerical value describing thermal insulation provided by clothing, ranging from 0.5 to 1.5, and is referenced by ASHRAE 55. In the context of modulating my attire to suit various activities, I judiciously selected distinct levels of clothing insulation from the reference provided by https://comfort.cbe.berkeley.edu/. Concurrently, for the assessment of metabolic rates aligned with my daily activities, careful consideration was given, with assigned values as follows: Sleeping (0.7), Reclining (0.8), Typing (1.1), Cooking (1.8), and Walking at 2 mph (2.0) (DiagramA.38).

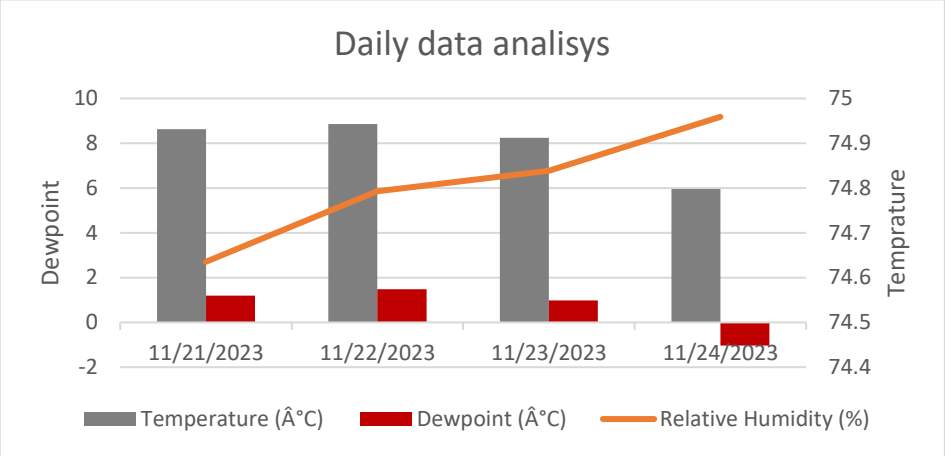


Diagram A. 38: Daily Data Analysis

3-Datalogger: From November 21st to November 25th, the data logger remained securely housed within a protective covering situated inside my backpack. The period is a four-day data collection period that encompasses pertinent parameters such as ambient temperature and relative humidity and, at this phase of the survey entails a quantitative analysis predicated on data obtained from a datalogger.

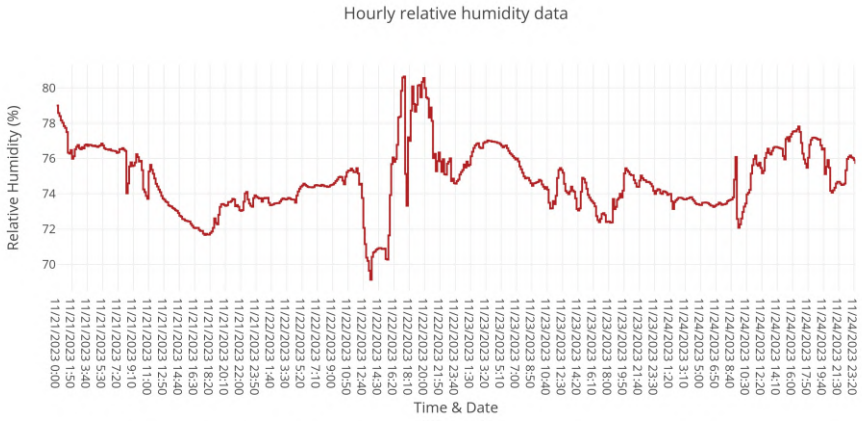


Diagram A. 39: Hourly relative humidity data

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The Datalogger showed the Relative Humidity changes between 69 to 80.

The observed temperature recorded by the indoor thermometer integrated into the heating system of my residence exhibited a slight variance in comparison to the temperature values registered by the data logger. It is conjectured that this discrepancy may be attributed to the environmental conditions influencing the data logger's storage.

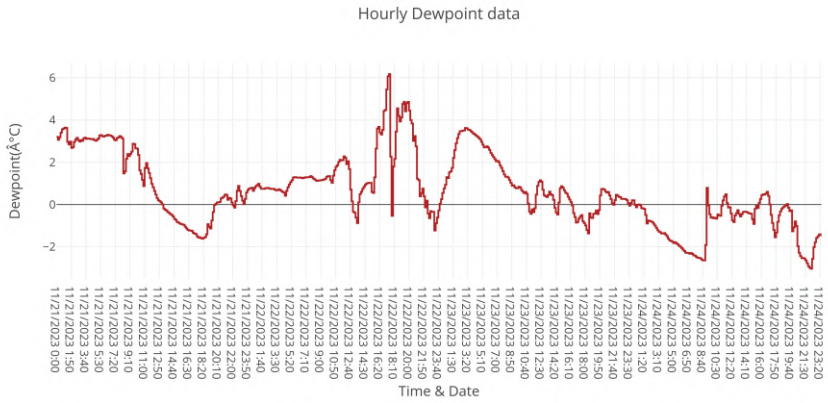


Diagram A. 40: Hourly Dewpoint data

The Datalogger showed Dewpoint (Â°C) changes between -3 to 6.

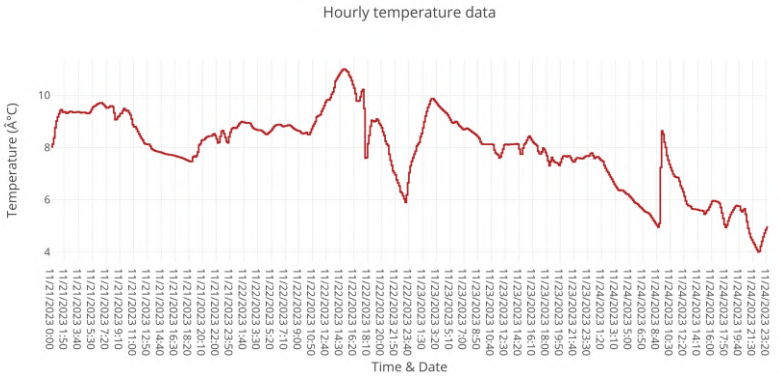


Diagram A. 85: Hourly temperature data

The Datalogger showed the temperature changes between 4 to 11.

My experience of the air inside my house is completely different from that of my housemates, and the hours when I feel warm at the same temperature, they suffer from cold, and this shows me that the feeling of cold and heat is completely dependent on people and is relative. To undertake this exercise, heightened scrutiny was directed towards the ambient surroundings and factors capable of influencing the subjective satisfaction with indoor air quality to investigate how much inevitably impacting work efficiency. A comparative analysis encompassed considerations such as attire selection, natural illumination, artificial lighting, and the reflective properties of wall colors (which contribute to alterations in luminosity). I prioritize cognitive engagement under conditions of subdued illumination with white lighting; Conversely, for recreational reading, the amber tint of a reading light contributes to an augmented sense of satisfaction. This observation elucidates the profound influence of specific activities on the subjective assessment of environmental quality and IEQ. The absence of windows in my office serves to enhance my concentration, as windows and the ingress of daylight have been identified as distractors impeding cognitive focus. The diminished concentration experienced in my domestic setting can be attributed, in substantial measure, to the presence of two windows in my room. Consequently, I find an augmented capacity for focused work within an environment devoid of windows. The coloration of my office walls, being light in hue, induces a perceived coolness and diminishes concentration levels. In contrast, the darker and warmer color of my

bedroom fosters a conducive environment for academic activities, enhancing my satisfaction with the space. This divergence highlights the influential role of color in shaping the psychological experience of interior spaces, particularly in its ability to modulate satisfaction levels.

A.3.2.4.5 Assignment 4 Title: Calculating the water footprint

Water is used to manufacture building products, during construction, and eventually consumed during building use. We must protect water from contamination by our buildings, yet water is also an environmental force from which we expect buildings to shelter us. In this assignment, I invite you to consider some of this complexity using a set of tools to measure the watery footprint of humans at various scales.
First, we had to consider our own water use to establish a foundation of knowledge and a baseline for comparison. Any number of online tools can tabulate the water demands of our lifestyle, but in this case, we had to use the extended version of the "Personal Water Footprint Calculator" one of the "Interactive Tools" found under "resources" at: http://waterfootprint.orgLinks to an external site. to calculate your water consumption. We had to pay attention to the questions focused on lifestyle (e.g. food, habits), rather than engineered systems or equipment.
Second, for a more design-based approach tied to buildings, we could consider specific fixtures and their use in a particular building, for example, our home or apartment. If we lived on-campus this may require a little bit of abstraction, or we could use a family home or other residence. In any case, do our best to develop a fair estimate of total water consumption. We might do this in several ways. We could develop a simple spreadsheet tallying each fixture in the house, its water consumption per use (often printed on it somewhere) and then count the frequency (check the box every time you flush!) or duration of use (time our shower with a stopwatch!) and multiply. We could borrow the calculation methodology for the water-efficiency credits in LEED for buildings, which makes assumptions based on empirical data. Alternatively, we might use a fixture-based on-line calculator like the one at https://www.home-water-works.org/Links to an external site.
Third to consider water at the scale of landscape, we could calculate water impacts at the site scale by using the EPA's National Stormwater Calculator, which estimates the annual rainwater and runoff for sites in the US based on soil conditions, cover, and rainfall records. we could download and install the desktop version or use the mobile/web version, both were available from: https://www.epa.gov/water-research/national-stormwater-calculatorLinks to an external site.
More important than simply adding up current conditions, the calculator makes it easy to compare alternative scenarios that include various low-impact developments that can affect what happens to stormwater on site. Our goal was to conduct that comparison and propose a range of appropriate strategies to improve that site in preparation for or conjunction with a sustainable building project.

• For the purposes of this exercise (and several others this semester) we considered the renovation/addition to a campus building, specifically Ryder Hall. So our site was on campus, with borders defined by Greenleaf Street to the North, Leon Street on the west, Ruggles Street to the south , the MBTA station and right-of-way to the south and east, and Forsythe Street to the east and North. In general we had to follow the center lines of streets when they are the border, as shown below:

- First, we had to use the calculator to develop a reasonable estimate of how the site handles stormwater now.
    - For most inputs we could use the default, or the soil-survey data provided in the tool.
    - For estimates of forest cover, lawn, impervious area, etc, we needed some kind of site plan from which to get areas. Google Earth https://www.google.com/earth/Links to an external site. has area calculation tools, which allow you to draw polygons over the satellite image to demark various surfaces and add up the areas so you can calculate a percentage of coverage.
    - Th teacher suggested measuring with more detail than the categories listed, for example, measuring the roofs, roads, and parking areas separately, and then adding them to calculate impervious area allowed us to calculate the LID controls later more easily by applying to only some percentage of that area, like the roof of one building, or all the parking but not the paths.
    - It was helpful to keep a spreadsheet/table with all the areas, particularly as we began applying combinations of LID Controls.
    - For this baseline, we could assume zero percent for all the LID Controls unless we already know some exist, such as downspouts that direct roof runoff onto grass.
    - On the last tab, calculate our results. we had to be sure to save this as a baseline.

Then, with our baseline, we had to go back and begin modifying the LIDs. Obviously, we could just make one LID treat 100% of the impervious area and pretend to be done. However, that was quite unrealistic, and obviously our objective in class is to learn about the different controls and their effects by realistically altering them. Also, we had to be sure we were only assigning green roofs to the percentage of impervious area that actually is roof. Experiment a bit to see which combinations yield the best (however we had to define that) results for this site. we had to answer this question: What package of improvements would we propose?

Finally, we compiled a brief report documenting your findings, including our results in all three parts of this assignment. The first two was fairly straightforward, numbers with a few sentences of description, but the third portion required some graphs and/or tables of data, and an illustration of the site plan showing the areas and labeled with the LID strategies you propose to use. The calculator had a lot of information and analysis available, and we did not need to present everything, instead, we curated the meaningful results and draw conclusions about the efficacy of the strategies for this site.



❖ Assimnets'4 Answer: Calculation the Water Footprint

Part 1:
Section 1: Calculation personal water footprint:
The result shows my water footprint is 1916.6 Cubic meter per year.

Based on your country of residence and your own consumption pattern, you will have a unique water footprint. Please feel free to use the footprint calculator to assess your own water footprint.

Country of residence	Iran, Islamic Rep of
Gender	◉ female
	○ male
Dietary habit	○ vegetarian
	◉ average meat consumer
	○ high meat consumer
Gross yearly income	3000 $ per year (only that part of the family income consumed by yourself)

Calculate my water footprint

Your water footprint is **1916.6 m³** per year.

Figure A. 59: input data

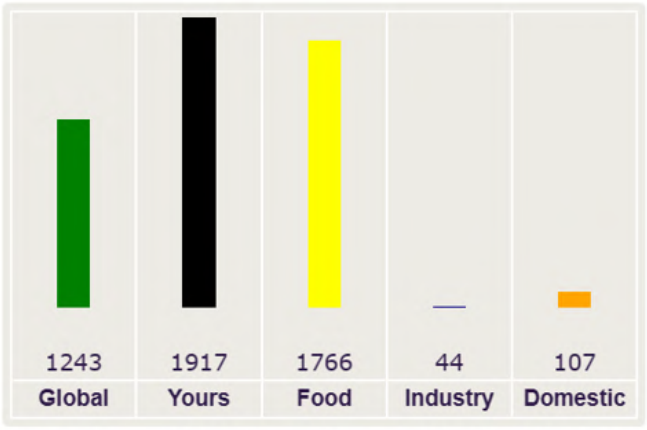


Diagram A. 42: Components of water footprint and comparison to the global average



Diagram A. 86: Categories within the food component of your water

Section 2:
Extend Calculate water footprint: My total water footprint is 622 cubic meters per year

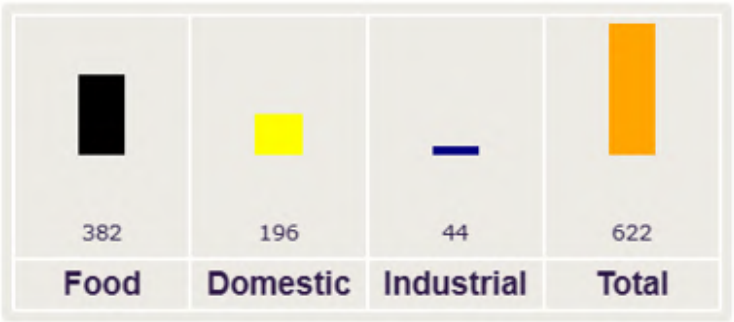


Diagram A. 44: Components of total water footprint

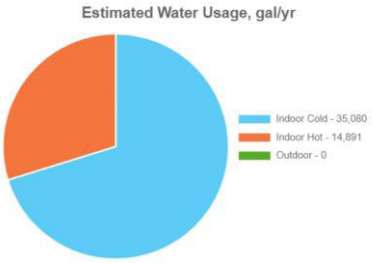


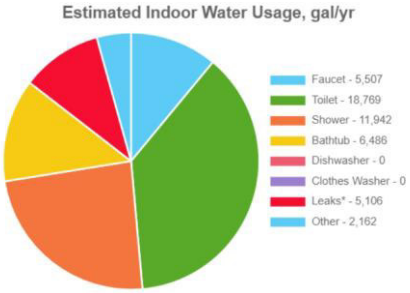
Diagram A. 87: Categories within the food component of water foot print

Part 2 :

The result shows that the most usage belong the indoor cold-water usage (Diagram 82)

Category	Gal per Year	Gal per Day	Gal per Person per Day
Faucet	5,507	15.1	7.5
Toilet	18,769	51.4	25.7
Shower	11,942	32.7	16.4
Bathtub	6,486	17.8	8.9
Dishwasher	0	0.0	0.0
Clothes washer	0	0.0	0.0
Leaks*	5,106	14.0	7.0
Other	2,162	5.9	3.0
Total indoor	49,971	136.9	68.5
Indoor hot	14,891	40.8	20.4
Outdoor	0	0.0	0.0
Total	49,971	136.9	68.5





Category	My House	Average House	Water-Wise House
Faucet	5,507	8,102	5,181
Toilet	18,769	13,683	4,616
Shower	11,942	9,336	9,336
Bathtub	6,486	966	966
Dishwasher	-	805	0
Clothes washer	-	11,858	0
Leaks*	5,106	6,654	5,106
Other	2,162	2,254	377
Total indoor	49,971	53,657	25,582
Indoor hot	14,891	15,990	7,623
Outdoor	-	0	0
Total	49,971	53,657	25,582
Carbon Footprint	2,171	2,331	1,111

Volume (gal/yr)

Category	My House	Water-Efficient House
Faucet	5,507	5,181
Toilet	18,769	4,616
Shower	11,942	9,336
Dishwasher	0	0
Clothes Washer	0	0
Leaks*	5,106	5,106
Outdoor	0	0

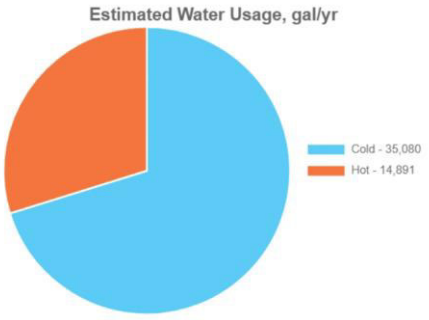


Diagram A. 88: Estimated Water Usage, Gal/yr

My efficiency recommendation:
Replace old toilets with water-sense labeled fixtures.
Install a water-sense-labeled showerhead and consider reducing the time spent in the shower.

A.3.2.4.6 Final Assignment: Environmental Product Declaration

A.3.2.4.6.1 Comprehensive elucidation of the subject matter

Over the past few decades, various assessment frameworks have been devised and put into operational use for sustainable construction practices. The Leadership in Energy and Environmental Design (LEED) system stands out as a prominent example in the

United States (Liu et al., 2019). As revealed by Daon et al.'s study in 2017, LEED has gained widespread recognition as the most versatile tool employed in 160 countries and territories, with a notable volume of scholarly literature dedicated to its examination. Notably, a substantial inclination among construction companies to certify their projects through LEED has been evident, as reflected in the primary journal sources analyzed since 1998 (Doan et al., 2017).

Studies indicate that properties certified by LEED exhibit a notable reduction in energy consumption ranging from 18% to 39% compared to their non-certified counterparts (Turner, Analyst, and Frankel 2008). However, the prevailing emphasis on credentials such as LEED, though impactful, tends to overlook the broader perspective of sustainability, as argued by Runde and Thoyre (Runde and Thoyre 2010). According to Berardi (2013) and Runde and Thoyre, sustainability's influence is anticipated to extend well beyond green buildings in the foreseeable future (Berardi 2013). Consequently, major green building rating systems, including LEED, have consistently updated their criteria to align with evolving sustainability principles. LEED underwent a significant overhaul in 2013 with the introduction of LEED v4 and subsequently updated its rating tools in mid-2016 (Doan et al., 2017). LEED (Leadership in Energy and Environmental Design) certifications and standards are periodically updated by the U.S. Green Building Council (USGBC) to reflect advancements in sustainable building practices, technology, and industry standards.

(Barbhuiya & Das, 2023).On November 3, 2022, during the annual Greenbuild International Conference and Expo, the U.S. Green Building Council (USGBC) revealed suggested revisions to the LEED v4 green building certification initiative with a more focused approach to addressing greenhouse gas emissions and climate change. These proposed updates involve elevating thresholds within LEED v4, aiming to stimulate enhanced energy performance and reductions in emissions. This adjustment is designed to bring LEED v4 more closely in line with the stringent criteria of LEED v4.1, which, upon its introduction in 2018, heightened the requirements for energy performance. LEED v4 initially concentrated on reducing energy demand through usage and efficiency, while LEED v4.1 introduced greenhouse gas emissions as a metric for building energy performance, a groundbreaking addition. Both LEED v4 and v4.1 address evolving market needs and build upon previous versions of the LEED rating system. With these changes, projects under LEED for Building Design and Construction (BD+C) and LEED for Interior Design and Construction (ID+C) can showcase energy performance improvements using metrics such as greenhouse gas emissions, cost, or source energy. The updated LEED v4 requirements will undergo a public comment period, with final approval subject to a vote by the USGBC membership. The changes will apply to projects registered after the effective date of the updates. The new rating system focuses on setting existing buildings on a decarbonization path and addresses equity, health, ecosystems, and resilience. Sept. 28, 2023 (Washington, D.C.) – the U.S. Green Building Council (USGBC) introduced a draft of its LEED v5 for Operations and Maintenance (O+M) rating system for existing buildings. LEED v5 is the newest version of LEED. It marks a transformative milestone in the built environment's alignment with a low-carbon future and addresses critical imperatives such as equity, health, ecosystems, and resilience. The LEED rating system is the world's preeminent green building certification system, with more than 100,000 projects certified globally. While the launch of LEED v5 begins with existing buildings, LEED v5 for Building Design and Construction (BD+C) will roll out in 2024. All the building's lifecycle could be evaluated By LEED based on the criteria from Building Design and Construction, Interior Design and Construction, Building Operations and Maintenance, and Neighborhood Development manuals. Points are how a building achieves LEED certification. The more efficient your building, the more points you earn. The more points you earn, the higher the certification level (certified, silver, gold, platinum). In this rating system,

many things are considered, including the selection of environmentally friendly materials. In fact, building materials play a significant role in environmental pollution throughout their life cycle, involving extraction, manufacturing, use, and disposal stages. The extraction of raw materials leads to environmental disruption, deforestation, and habitat destruction, with associated pollutants from mining operations impacting ecosystems and local communities. Manufacturing processes contribute to environmental impact through energy consumption, greenhouse gas emissions, and the release of pollutants into the air and water. Transportation and distribution add to pollution with carbon emissions and air pollutants from fossil fuel usage. Construction and use phases generate pollution from noise, dust, and energy consumption, potentially releasing pollutants into the air and water, and affecting local ecosystems. The end-of-life and disposal phases contribute to landfill usage and environmental degradation, posing risks from improper disposal of hazardous substances. Some materials also introduce harmful chemicals, contributing to both indoor and outdoor air pollution(Barbhuiya & Das, 2023). Mitigation efforts focus on sustainable practices, including recycled materials, eco-friendly manufacturing, energy-efficient designs, and materials with lower environmental footprints. Green building certifications, such as LEED, underscore the importance of material selection aimed at minimizing pollution throughout the entire life cycle.

Therefore, growing recognition of the need for standardized and transparent information about the environmental impacts of products, particularly in the context of sustainability and green building initiatives lead to the emergence of Environmental Product Declarations (EPDs). Environmental Product Declarations (EPDs) play a significant role in helping buildings earn credits in the LEED (Leadership in Energy and Environmental Design) certification process.

Environmental Product Declarations (EPDs) are relatively recent, with a history of just 16 years, having originated from the ISO 14025 standard titled "Environmental labels and declarations — Type III environmental declarations — Principles and procedures," first published in 2006. This standard provides foundational guidelines for creating EPDs based on life cycle assessments (LCAs).

The growing recognition of the imminent threat of climate change serves as the overarching factor driving the adoption of EPDs. However, more immediate influences contributing to the current sense of urgency include financial market dynamics, government policies mandating EPDs for construction through 'buy clean' initiatives, and the requirements of global developers like Amazon and Microsoft, who insist on the use of EPDs in their international projects. These influences are unfolding at varying paces and in distinct ways across Europe, the Americas, and Asia. Nevertheless, the collective global outcome is a sustained emphasis on sustainability, with EPDs serving as essential tools to measure reductions in Global Warming Potential (GWP). The convergence of these factors reflects a global commitment to environmental responsibility and a standardized approach to assessing and addressing the environmental impacts of products.

A transparent and standardized method for manufacturers to inform customers, companies, and other stakeholders about the environmental performance of their products is through the Environmental Product Declaration (EPD). Providing unbiased, fact-based information on a product's environmental effect at every stage of its lifecycle—from raw material extraction to manufacture, usage, and disposal is the main objective of an environmental product declaration (EPD). The main objectives of an environmental product declaration are to offer precise, reliable, and consistent data regarding a product's environmental impact, assist consumers and businesses in making environmentally conscious decisions, and encourage sustainability in the design and production of products. Some main goals and advantages of environmental

product declarations are Transparency, Environmental Awareness, Market Differentiation, Life Cycle Assessment (LCA), Supply Chain Improvement, and Sustainability Reporting. Through encouraging life cycle thinking, boosting transparency, encouraging the use of environmentally friendly products and materials, and incentivizing positive changes in the manufacturing and construction industries, obtaining EPD credits in sustainable building certification programs contributes to the improvement of building sustainability. It advances sustainable construction processes and lessens the total impact of buildings on the environment.

A more sustainable, functioning, and ecologically conscious construction industry would result from every building achieving EPDs for its goods and materials. It would encourage innovation, lessen the negative effects of buildings on the environment, and bring the construction industry closer to the goals and objectives of sustainability. Depending on the certification program and the credit criteria, several evaluation methods may be used. Certification programs frequently have comprehensive program paperwork that outlines the documentation and verification process. They may also have their own set of rules and assessment criteria. The purpose of the EPD-related credit evaluation procedure is to verify that the project team has really utilized EPD-certified materials and products and that the building's environmental performance complies with the certification program's sustainability objectives and criteria. A mix of evidence submission, computations, third-party review, and site visits to verify compliance may be used in this process. Due to increasing awareness of the environment and the demand for transparent, eco-friendly, and sustainable products, the EPD credit has evolved from LEED 2.2 (2005) to LEED V4. (2023).
Besides all the positive features of EPD, there are some problems with EPDs still. For professionals in the construction industry, such as architects and planners, EPDs serve as a crucial foundation for thorough planning and building appraisal. However, because a construction product's level of sustainability, resource conservation, or environmental friendliness depends heavily on the (building) context in which it is utilized, EPDs are typically not appropriate for direct product comparisons.

A.3.2.4.6.2 A review of the content

A.3.2.4.6.3 Description and Definition

The abbreviation EPD is derived from the English term Environmental Product Declaration and is usually translated into German as Umwelt-Product declaration. An EPD is a document in which the environmentally relevant properties of a product are outlined in the form of neutral and objective data. This data covers as many impacts as possible that the product can have on its environment, whereby in an ideal situation, the entire life cycle of the product is taken into consideration (https://www.environdec.com/). An Environmental Product Declaration (EPD) is a standardized document informing about a product's environmental and human health impact. It's based on the ISO 14025 standard and the scientific footprinting method Life Cycle Assessment (LCA). The goal of an EPD is to inform and communicate with stakeholders about a product's environmental impact.
Therefore, companies often use EPDs for commercial purposes. An EPD is produced on the basis of LCA calculations and provides a quantitative basis for the comparison of products and services. An LCA calculates the environmental footprint of a product throughout its lifecycle – expressed in 15+ impact outcomes. It is possible to create an EPD for a company-specific product or for the average product of members of a branch organization. An EPD is normally provided by the product manufacturer and must be verified by an independent expert. An EPD normally has a validity of 5 years. The

basis of an EPD is the norm ISO 14025. This norm calls EPDs Type III environmental declarations – also Type III EPDs (https://ecochain.com/).
(Wang & Su, 2022).In addition, environmental declarations are becoming increasingly important to communicate data on the environmental impacts of products in the supply chain. The International EPD System (EPD) summarizes details of the environmental impacts of the product such as global warming potential, for each aspect of the product's life cycle (Wang & Su, 2022). the PCRs give instructions to the content of the EPD (Fet, Skaar, and Michelsen 2009) More specifically, environmental declarations are a standardized type of LCA study that allows comparisons between products that perform the same function. There are a variety of environmental declaration programs in different industries, such as The Eco-Profile, Environmental Profiles, Product Environmental Profiles (PEP), etc. The legal requirement in the European market is Regulation (EC) No. 66/2010 (Ecolabel Regulation), which has been adopted by the major companies. Most carbon footprint certification tools, whether by a third party or a company working on its products, rely on a range of LCA approaches and data: The Carbon Reduction Institute offers a carbon-neutral certification scheme (Whittaker, McManus, and Smith 2013)
As a summary, Environmental Product Declarations is essentially a thorough report that uses a Life Cycle Assessment (LCA) to transmit environmental facts about a product in a standardized manner. A well-developed EPD follows ISO standards, guaranteeing a comprehensive display of environmental data throughout the product's life cycle, including quantitative assessments of major impacts. EPDs identify the environmental consequences of a product in a specified format established in an ISO-compliant Product Category Rule (PCR) and certified by the PCR program operator. EPDs enable designers, specifiers, purchasers, code authorities, and the public to understand both the particular and overall environmental implications of a product by providing information from cradle to grave (or cradle). EPDs make the environmental benefits of energy efficiency and other important aspects of a given product clearer. An EPD is not a claim of environmental superiority for a specific product (https://www.greenbuildingsolutions.org/). Recent green public procurement (GPP) initiatives in the U.S.A. rely on the use of the construction materials EPDs. EPD programs, however, were initiated by the material manufacturers, motivated by their interest in using EPDs as communication tools, improving production efficiency, and extending outreach. The use of EPDs that ensures environmental improvements of materials is contingent on EPD consistency and PCR prescriptiveness. EPDs can be suitable as data sources in pavement LCA due to their availability, and transparency, and because they facilitate collaboration and improvements throughout the supply chain (Rangelov et al., 2021).

The increasing adoption of environmental product declarations (EPDs) in the construction industry raises questions about their appropriateness and impact on the wider industry. Gelwitz et al in 2018 have done a case study that explores the use of EPDs in construction projects, focusing on stakeholder perspectives. Contractors express concerns about timeline impacts, while designers highlight limited transparency. The integrative design process is crucial for project success, avoiding long lead times and close specification review (Gelowitz and McArthur 2018). In this study Several key issues arose as part of this interview process of relevance for new projects intending to use EPDs as part of the construction process. There are challenges in product sourcing, the appropriateness of using EPDs to compare similar products, and potential schedule impacts arising from product limitations. It did not seem that practitioners were concerned with the comparability and level of harmonization between EPDs.

The Designer put more importance on the information within the EPDs to make decisions about a specific product within the context of the whole-project LCA, rather than using the EPDs to make product comparisons. At a stage of the infancy of use in the construction industry where declared products are scarce, this was considered the most suitable way to use EPDs. Small- to medium-sized firms are constrained in developing EPDs because of resource and people limitations (Fet et al. 2009). LCA- and EPD-information is used by practitioners in different applications and that there may be a need to increase standardization efforts of benchmarking procedures in order to improve communication with non-specialist audiences (Galindro et al., 2020).

Credit for EPD

EPDs play a role in helping a project earn credits within the LEED certification system. In the context of LEED, incorporating materials with low environmental impact, as evidenced by EPDs, can contribute to meeting specific criteria or prerequisites set by LEED for a project to earn credits. These credits are part of the overall point system in LEED, which is used to determine the level of certification a building can achieve (Certified, Silver, Gold, or Platinum). Therefore, by utilizing materials with EPDs that demonstrate environmentally friendly characteristics, a project can enhance its chances of earning credits within the LEED certification system, ultimately contributing to the project's overall sustainability and environmental performance. Here's how EPDs contribute to receiving credits in LEED:

Materials and Resources (MR) Credits:

MRc1 - Building Life-Cycle Impact Reduction:

The function of EPD: EPDs provide detailed information about the environmental impacts of building materials throughout their life cycle. This information helps project teams make informed decisions to minimize the overall environmental impact.

MRc2 - Building Product Disclosure and Optimization: Environmental Product Declarations:

The function of EPD: EPDs are directly referenced in this credit. Projects can earn points by using products with EPDs, as EPDs provide a standardized way of reporting the environmental impact of materials.

MRc3 - Building Product Disclosure and Optimization: Sourcing of Raw Materials:

The function of EPD**:** EPDs can contribute to points in this credit by providing information about the sourcing of raw materials used in the production of building products.

Innovation in Design (ID) Credits:

IDc1 **-** Innovation in Design:

The function of EPD: Projects may earn Innovation in Design credits for using innovative strategies that go beyond the standard requirements. Integrating EPDs for materials can be considered an innovative approach toward sustainable building practices.

General Contributions:

Transparency and Disclosure: EPDs contribute to transparency by disclosing information about a product's environmental performance. This aligns with LEED's emphasis on providing transparent information for making sustainable choices.

Market Transformation: The use of EPDs promotes market transformation by encouraging manufacturers to produce products with lower environmental impacts. This shift in market demand toward more sustainable materials contributes to broader sustainability goals.

EPDs play a vital role in LEED certification by providing valuable information about the environmental impact of building materials. This information is used to make informed decisions that align with LEED's sustainability goals, and the use of products with EPDs is directly recognized and rewarded through specific credits in the Materials and Resources category and potential Innovation in Design credits.

Tim line

In 2005, when LEED 2.2 emerged on the green building scene, a subtle nod to sustainability was born. The first iteration of the EPD credit, nestled within MR Credits 4.1 and 4.2, whispered encouragements for the utilization of materials containing recycled content. This marked the humble beginnings of a journey towards a more environmentally conscious construction industry. As the years unfolded, so did the evolution of the EPD credit. By 2009, LEED 2.2 had grown wiser, reflecting the development of sustainable materials. Credit expanded its scope to encompass a variety of facets, embracing not only recycled content but also the swift renewal of materials, as seen in the refined MR Credit 4. The paradigm shift continued with the advent of LEED v4 in 2013, where the MR Credit titled "Building Product Disclosure and Optimization (OPT1)" witnessed a substantial enhancement of the EPD credit. This augmentation manifested in a strategic emphasis on the promotion of products endowed with life cycle assessments and third-party validated environmental product declarations, underscoring a heightened commitment to comprehensive environmental considerations. In the subsequent iteration, LEED v4.1 (2016), the rating system reached a new zenith in its commitment to sustainable practices. It facilitated the advancement of the EPD credit by introducing options for whole-building life cycle assessments (LCA) and streamlining the intricate process of accruing points for EPDs. This marked a pivotal moment in rendering the certification process more accessible and pragmatic for stakeholders. The year 2018 bore witness to LEED 4.1, wherein the encouragement of products featuring EPDs persisted, complemented by the seamless integration of whole-building life cycle assessments. The EPD credit maintained its fundamental status within the materials and resources category, reflecting a sustained dedication to promoting environmentally conscious material choices. In the ensuing years, LEED V4.1 (2020) continued its trajectory of refinement, with additional improvements to the EPD credit and an unwavering commitment to ongoing scrutiny of life cycle analyses pertaining to materials and products, with a specific emphasis on EPDs. Looking towards the future, LEED V4. (2023) portends potential changes, as proposed alterations to LEED 4.1 or the introduction of a new version may herald additional improvements in the EPD credit, alongside enhancements in other standards pertaining to sustainable materials. This continuous evolution underscores the dynamic nature of LEED's pursuit of sustainable building practices and its responsiveness to industry advancements and environmental imperatives.

EPD included.

To guarantee consistency and reliability in the information supplied, EPDs are usually created in accordance with international standards and guidelines, such as ISO 14025 and EN 15804.

Typically, an EPD should contain the following data:

- Product Description: Details about the product, such as its name, maker, and an overview of its features and intended use.
- Life Cycle Evaluation (LCE): This section gives information on the product's environmental effect at every stage of its lifetime, from extraction and manufacture of raw materials to usage, transportation, and disposal at the end

of its useful life. Data on emissions, resource usage, energy consumption, and other environmental aspects could be included.

- Functional Unit: By defining the precise amount or performance of the product on which the EPD is based, the functional unit facilitates the comparison of other items that serve comparable purposes.
- System Boundary: In this section, the processes and activities that are part of the assessment are specified, along with the scope of the life cycle assessment (LCA). It aids in defining the analysis's parameters.
- Impact Categories: EPDs usually include information on a range of environmental impact categories, including energy use, water use, greenhouse gas emissions, and more. These categories aid consumers in comprehending how the product affects the environment in relation to many factors.
- Data and outcomes: EPDs contain data and outcomes in numerical form pertaining to the product's environmental performance. To facilitate comparison and interpretation, this data is frequently shown as tables or charts.
- Assumptions and Methodology: To ensure openness and help users comprehend the foundation for the data and outcomes, EPDs detail the procedures and presumptions utilized to conduct the LCA.
- Environmental Declarations: Environmental performance declarations (EPDs) often include details regarding a product's water and/or carbon footprint footprints, among other pertinent metrics.
- Additional Information: Any pertinent information that might assist users in understanding and utilizing the EPD more skillfully can be provided in this area, along with any supplemental data or explanations.

Benefits and advantages (objectives and goals)

Earning Environmental Product Declaration (EPD) credits in sustainable building certification programs like LEED or BREEAM can enhance a building's sustainability. EPDs provide information on the environmental impacts of building materials and products, enabling architects and builders to use materials with lower environmental footprints. They also encourage a holistic approach to building design and construction, reducing the environmental impact over its lifetime. Prioritizing EPDs can lead to market transformation, increasing demand for environmentally responsible products, enhancing transparency and accountability, and achieving higher certification levels. EPDs can also raise user awareness, leading to more responsible resource use and sustainability practices. Earning EPD credits is crucial for organizations with sustainability goals, demonstrating a commitment to reducing environmental impact (https://www.intertek.com/).

The following are some main goals and advantages of environmental product declarations:

- Environmental Awareness: By bringing disclosure of a product's environmental effects, EPDs assist businesses and consumers in making more environmentally friendly decisions.
- Market Differentiation: If a manufacturer's product has a lesser environmental effect than that of a competitor, they can apply EPDs to set themselves apart from other businesses.
- Transparency: A product's environmental performance is fully disclosed and made transparent through EPDs. This makes it possible for companies and customers to compare items according to their environmental qualities and make educated decisions.

- Sustainability Reporting: To show a dedication to environmental responsibility, EPDs can be linked into sustainability reports and CSR projects.
- Supply Chain Improvement: Since EPDs point out opportunities for improvement, manufacturers may utilize them as a tool to evaluate and enhance the environmental performance of their supply chains.
- Environmental legislation and Standards: EPDs can assist businesses in adhering to environmental legislation or industry standards, which may mandate them or promote their use.
- Conscious Decision-Making: Using the information provided by EPDs, architects, designers, and procurement specialists may make choices that support their goals for sustainability.
- Life Cycle Assessment (LCA): A life cycle assessment, which takes a product's environmental effect into account from cradle to grave, is the foundation for EPDs. By taking a comprehensive approach to a product's life cycle, false claims of environmental friendliness known as "greenwashing" are less likely to occur and chances for improvement are more easily found.

Through encouraging life cycle thinking, boosting transparency, encouraging the use of environmentally friendly products and materials, and incentivizing positive changes in the manufacturing and construction industries, obtaining EPD credits in sustainable building certification programs contributes to the improvement of building sustainability. It advances sustainable construction processes and lessens the total impact of buildings on the environment (https://www.archtoolbox.com/).

The effect of EPD on sustainability

The adoption of Environmental Product Declarations (EPDs) for construction materials and products could significantly reduce environmental impact, promote transparency, drive market transformation, improve sustainable building certification, enhance user awareness, spur innovation, influence policy and regulatory impact, and have positive economic and health effects. EPDs provide detailed information about the environmental performance of materials, enabling builders and architects to make more sustainable choices. This transparency promotes accountability and responsible decision-making, leading to a more sustainable supply chain and industry. The increased demand for sustainable building materials and products would also lead to increased investment in research and development, promoting continuous improvement in sustainability. The widespread adoption of EPDs could also influence policymakers to create regulations and incentives supporting environmentally responsible construction practices (Andersen et al., 2019).

A.3.2.4.6.4 Measure or provide as proof to indicate meet the required standards.

In the context of sustainable building certification programs such as LEED or BREEAM, project teams aiming to get credits connected to Environmental Product Declarations (EPDs) usually must furnish proof of their adherence to the credit prerequisites. Depending on the certification scheme, the precise proof needed may change, but project teams may measure or present the following factors to prove they have earned the credit or not:

1- EPD documentation: Project teams are required to submit documentation attesting to the EPDs that are being used. This can contain the actual Environmental Product Declarations (EPD) for every

product, which describe the materials' effects on the environment and how well they adhere to applicable regulations.

2- Use of EPD-Certified products: The project groups are required to provide evidence that, relative to the total amount of construction materials or goods, they have utilized a specific percentage of products and materials with EPDs. The list of these materials and the EPDs that go with them would be part of the proof.
3- Compliance with Credit Thresholds: A particular percentage of materials with EPDs, for example, maybe one of the certification programs' objectives or thresholds for the usage of EPDs. Calculations demonstrating how the project meets or surpasses certain limits may be used as evidence.
4- LCA (Life Cycle Assessment) Data: Project teams could occasionally be asked to submit LCA data that illustrates how environmentally friendly the products and construction materials are. Claims regarding the building's decreased environmental effect can be supported by this evidence.
5- Estimates and Reporting: Project teams are frequently required by certification programs to submit calculations and reports that demonstrate how the products and materials used to improve the building's environmental performance, particularly in terms of energy efficiency, fewer greenhouse gas emissions, or additional environmental sustainability measurements.
6- Project Parameters: To guarantee that the selected materials and products fulfill the requirements, EPD requirements may be included in the project specifications or contracts.
7- Third-Party Verification: Third-party certification or verification of the EPDs utilized in the project may be required by some certification schemes. To prove compliance with the credit, proof of this verification could be required.
8- Construction and Procurement Records: To demonstrate that the designated EPD-certified items were really utilized, project teams may be required to submit records and paperwork pertaining to the acquisition of goods and materials, including as purchase orders and invoices.
9- Audits and Inspections: To ensure that the EPD-related requirements have been fulfilled, certification programs may call for project teams to participate in audits or inspections.
10- Written Evidence: To satisfy the EPD-related credit criteria, project teams normally must submit written documentation or a narrative outlining the actions they took to guarantee the use of environmentally friendly products.

Different certification programs have varying criteria for proof types, so project teams should consult the program's rules and paperwork to determine the required evidence for EPD-related credit. This evidence may be examined and verified by program administrators or outside assessors as part of the certification process.

A.3.2.4.6.5 A.3 Assessment method

Depending on the certification program and the credit criteria, several evaluation methods may be used. Certification programs frequently have comprehensive program paperwork that outlines the documentation and verification process. They may also have their own set of rules and assessment criteria. In the end, the purpose of the EPD-related credit evaluation procedure is to verify that the project team has really utilized

EPD-certified materials and products and that the building's environmental performance complies with the certification program's sustainability objectives and criteria. A mix of evidence submission, computations, third-party review, and site visits to verify compliance may be used in this process.

The overarching goal of encouraging environmentally conscious and sustainable construction methods is aligned with the measurement and evidence criteria for obtaining Environmental Product Declaration (EPD) credits in sustainable building certification schemes. The proof submission procedure generally seeks to guarantee that project teams are using goods and resources that have less of an impact on the environment, which is consistent with the objectives and advantages of EPDs for the environment. To achieve the desired environmental advantages, the measurement and proof criteria are typically regarded as trustworthy for the following reasons:

In the area of construction, EPDs represent an essential basis for experts such as architects and planners when it comes to the comprehensive planning and evaluation of buildings. However, EPDs are not usually suitable for direct comparisons of products as the degree of environmental friendliness, conservation of resources, or sustainability displayed by a construction product is largely dependent on the (building) context in which it is used. Just how environmentally friendly, resource-saving, or sustainable certain products or materials are also largely dependent on the buildings in which they are installed and/or used. Example: An igloo is typically built by hand using a single construction material: snow – an environmentally friendly, natural product that can be recycled in full. From this perspective, snow as a building material and the actual igloo building are sustainable – ecologically. However, this is not universally applicable but only under certain conditions. After all, if we wished to build an igloo in our climate zone or even in the tropics where there is little or no snow, the snow would have to be produced or imported at great energy expenditure. What's more, the igloo would melt after only a short period of time if it was not cooled or permanently replaced. It goes without saying that this is a very simplified example, but it does illustrate why construction products are not end products and that the influence they have on the environment is largely dependent on how, where, and what they are used for. For this reason, construction products that initially appear environmentally friendly are by no means a guarantee of sustainability. And that is why we have EPDs. They contain the data required for calculating and evaluating environmental influences in specific cases.

A.3.2.4.6.6 How EPD helps the product to meet the sustainable goals

Life cycle assessment of construction products

EPDs do not simply contain random estimates or arbitrary numbers. They are based on life cycle assessments of construction products. A life cycle assessment summarizes and analyses the environmental impacts of a certain product across its life cycle, from the provision of raw materials to the finished product ready for installation. Processes and factors associated with the product are also taken into consideration, e.g. packaging and transport. Increasingly, other phases of the life cycle are also considered, e.g.use phase, recycling, reuse, and disposal (https://www.greenbuildingsolutions.org/).

One particularly important feature of life cycle assessments is the fact that they do not deliver a single parameter or assessment but rather individually depict a variety of different environmental influences. For example, apart from greenhouse gas emissions, other influencing factors such as acid rain, smog formation, consumption of fossil resources and water or recycling percentages are also considered. All this information is included in EPDs which means that it is publicly available – after all, truly

sustainable solutions can only be found by simultaneously considering as many environmental impacts as possible

life cycle assessments of buildings

The life cycle assessment of a building essentially comprises two parts: the life cycle assessments of all construction products and materials used as well as energy consumption during the use phase of the building. Accordingly – and as for individual products – the environmental impacts of an entire building can be calculated across its entire life cycle, i.e. from the provision and production of materials through the construction and use phase to de-construction of the building. Calculating the life cycle assessment of a building during its planning phase makes it possible to compare various materials and concepts from an ecological perspective and thereby improve the building. While direct comparisons of various construction products and their life cycle assessments is usually less practical, comparing them within the framework of building life cycle assessments is an essential basis for planning sustainable structures. Life cycle assessments are, therefore, mandatory in some certification systems for sustainable buildings (e.g. at Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB), https://www.dgnb.de/).

The increasing significance of EPDs due to higher energy efficiency.

When considering the environmental impacts of a building across its life cycle, two phases are of particular importance: the use phase, i.e. during operation, and the construction phase which also includes the provision and manufacture of materials. Modern buildings are increasingly energy-efficient: they use less energy during operation which also reduces their overall energy requirements. Accordingly, there is a shift in the percentages of overall energy requirements accounted for by the use phase and the construction phase – and this is accompanied by a shift in their share of environmental impacts by the building. For example: energy requirements during the operation of older buildings (built before 1977) cause more than 90 percent of all greenhouse gas emissions of a building, i.e. less than 10 percent of its greenhouse gases are attributable to the construction phase. In modern low-energy buildings, energy requirements during operation are significantly lower – which also means lower greenhouse gas emissions overall – with the result that the use phase is only responsible for around 60 percent of greenhouse gases, and the construction phase accounts for 40 percent. The impact of the construction phase on the (overall lower) environmental impact of the building is therefore doubled. In the case of a truly zero-energy building, the construction phase would even account for 100 percent of total greenhouse gas emissions. As energy efficiency improves, the relative influence of the construction phase also increases – and this is accompanied by an increase in the significance of EPDs, as only they permit a scientific and reliable evaluation of the construction phase and the environmental influences associated with it. **How EPDs fit into the space and time of sustainable construction**:

The influence of Environmental Product Declarations (EPDs) on the building and construction sector is felt throughout a structure's life cycle. Architects and designers use EPDs to influence material decisions throughout the design process, considering environmental implications and matching choices with sustainability goals. EPDs go beyond specific product evaluations to contribute to whole-building assessments, providing a full picture of the environmental performance of a project. EPDs affect procurement procedures throughout the building phase, allowing contractors to pick materials with lower environmental effects, boosting overall project sustainability

through decreased waste and energy use. The operational efficiency of a building is impacted by prior decisions on energy-efficient technologies during the usage phase. EPDs give data on recyclability and disposal throughout the end-of-life phase, assisting in the safe management of materials during deconstruction. The societal and environmental consequences include resource-saving, environmental degradation prevention, and market change as the widespread usage of EPDs stimulates manufacturers to design more environmentally friendly goods. Furthermore, EPDs help to raise awareness and education, encouraging an ecologically conscientious business and client base (Rangelov et al., 2022).

5.8.4.1.1.1 Conclusion

In conclusion, since EPDs support the use of environmentally friendly materials and transparent, informed decision-making, the measurement and evidence requirements for obtaining EPD credits are generally reliable in correlating with the achievement of environmental benefits aligned with the purpose and objectives of EPDs. To improve their efficacy in advancing sustainability in the construction sector, these rules may need to be continuously assessed and refined. The construction business and sustainability would both benefit if every building attained Environmental Product Declarations (EPDs) for the products and materials used in construction. Here are a few possible outcomes:

1. Diminished Environmental effect: The environmental effect of building development would be significantly reduced if EPDs were widely used. With access to comprehensive data on the environmental performance of materials, architects, and builders would be able to make more environmentally friendly decisions, such as choosing low-impact materials, streamlining designs, and cutting waste.
2. Transparency: Since all parties involved would have access to information on the environmental impact of each building component, the construction industry would become more open. Accountability and responsible decision-making would be encouraged by this honesty, which would support sustainable practices across the business.
3. Market Improvement: There would be a rise in the demand for building supplies and goods that are ecologically friendly. Manufacturers would therefore be encouraged to create more environmentally friendly products and make investments in more eco-friendly production techniques. The industry as a whole and the supply chain would become more sustainable because of this market shift.
4. Beneficial Effects on the Economy and Public Health: The implementation of EPDs may have a beneficial influence on the economy and public health by lowering environmental consequences like carbon emissions and pollution of the air and water. Healthcare expenditures can be lowered, and the environment can be cleaner with less pollution and resource usage.
5. Superior Sustainable Building Certification: Projects that use materials with EPDs are rewarded by several sustainable building certification schemes, including BREEAM and LEED. A greater commitment to sustainability would be shown by more buildings becoming eligible for higher certification levels because of broad EPD adoption, which would also encourage developers to pursue higher certification levels.
6. Increased User Knowledge: Building users and occupants would learn about the environmental effects of their surroundings from the

information that EPDs give. This knowledge may encourage more sustainable and resource-conscious building methods, both in the early stages of development and during the structure's lifetime of use.

7. Research and Creativity: The sector would see a surge in innovation because of the growing demand for sustainable building supplies and materials. Manufacturers would spend money on R&D to produce more eco-friendly, high-performing products, which would increase sustainability over time.
8. Legislative and Regulation Impact: If EPDs are widely used, legislators may be persuaded to enact laws and provide incentives that promote ecologically friendly building methods. At the regulatory level, this may result in more stringent environmental requirements and a more environmentally conscious building sector.

It's crucial to remember that the specifics of the credit criteria, the strictness of the certification process, and the vigilance of project teams and manufacturers may all have an impact on how successful it is to achieve environmental advantages through EPD credits. Sustainable building certification organizations regularly assess and update their standards for proof compatibility with the desired environmental goals, since there may be opportunities for improvement in some circumstances.

A.3.2.4.6.7 Suggestion for future

Improving the efficacy of Environmental Product Declarations (EPDs) in promoting sustainable construction necessitates a holistic strategy. Among the key goals is the creation of a comprehensive database of up-to-date EPDs for various construction goods, which will serve as a helpful resource for individuals looking for sustainable solutions. Encouragement of EPD reporting standards improves the dependability and comparability of environmental data, promoting uniformity across varied goods and sectors. Educating architects, contractors, and consumers on the importance of EPDs increases demand for environmentally friendly products. Integrating EPD data into design tools enables professionals to make real-time decisions and choose materials with minimal environmental implications. Incentivizing manufacturers to create EPDs through certification programs or government efforts encourages transparent reporting and environmentally beneficial practices. The use of technology, such as blockchain or digital platforms, assures the traceability and transparency of EPD data. Environmentally friendly items are encouraged to be used because of government rules requiring EPDs for building projects and incorporating them into public procurement strategies. Promoting life cycle thinking in design and building processes encourages project teams to evaluate materials' whole life cycle, from extraction to disposal. Collaboration among industry stakeholders, including manufacturers, architects, and legislators, promotes the creation of effective and generally recognized EPD standards. Finally, pushing for ongoing development in EPD procedures and reporting standards, in tandem with advances in environmental assessment methods, increases the influence of EPDs on sustainable buildings. Overall, such efforts help to educate decision-making, promote demand for eco-friendly goods, and move the building sector toward a more sustainable future.

A.4 Exceptional Academic Infrastructure

During my tenure at Northeastern University, I had the privilege to explore and interact extensively with its exceptional academic infrastructure, particularly within the Architecture department. This experience afforded me a comprehensive view of the

innovative teaching methodologies and state-of-the-art facilities that define the institution's commitment to academic excellence.

The Architecture department, known for its rigorous curriculum and forward-thinking approach, provided insightful exposure to advanced design theories and practical applications. I observed a variety of teaching methods, ranging from traditional lectures and seminars to hands-on workshops and collaborative projects, all designed to nurture creativity and critical thinking. The department's integration of technology in education was particularly impressive, leveraging cutting-edge software and digital fabrication tools to enhance learning and research.

Furthermore, the physical environment of the university, with its modern classrooms, well-equipped laboratories, and resource-rich libraries, significantly enriched the educational experience. These facilities not only supported the academic pursuits of students and faculty but also fostered an atmosphere of innovation and discovery.

Interacting with the faculty and students from different departments, I witnessed a vibrant academic community where interdisciplinary collaboration and cross-pollination of ideas were the norm rather than the exception. This holistic educational ecosystem at Northeastern University not only cultivates academic prowess but also prepares students to be adaptable and impactful in their future careers.



Figure A. 60: Department of Architecture, Department of Agriculture

A.5 Conclusion:

In conclusion, my time at Northeastern University in Boston significantly enriched my academic and professional journey, particularly in the realm of architectural principles and regenerative design of spatial structures aimed at achieving positive buildings. The three core aspects of my experience—interaction and communication, scientific approach, and exceptional academic infrastructure—interplayed to profoundly influence my scientific approach and thesis work.
Firstly, interaction with the diverse scientific community at Northeastern provided me with invaluable insights and broadened my perspective, enabling a deeper

understanding of my field. Communication with peers and faculty across various disciplines fostered a multidisciplinary approach, crucial for the holistic understanding required for regenerative design in architecture.

Secondly, the scientific approach I was immersed in at Northeastern honed my research and analytical skills. Engaging with rigorous academic methodologies and empirical research has sharpened my ability to question, analyze, and synthesize complex concepts, directly contributing to the robustness of my thesis.

Lastly, the exceptional academic infrastructure, including access to cutting-edge software and learning environments, allowed me to practically apply and test theoretical frameworks. This hands-on experience was instrumental in developing a practical understanding of the architectural principles necessary for creating sustainable and regenerative spatial structures.

Overall, my activities during the two semesters at Northeastern University have had a profound impact on my scientific approach, equipping me with the tools, knowledge, and perspective necessary to advance my thesis. The integration of interaction, scientific rigor, and state-of-the-art infrastructure has not only enhanced my research capabilities but also positioned me to contribute meaningfully to the field of sustainable architecture.

Appendix B
Publications and Scholarly Outputs

B.1 Regenerative Architecture in Practice: A Multifaceted Exploration of Cladding systems to meet LEED standards (Energy & Buildings Journal)

B.1.1 Abstract

Given the significant impact of the construction sector on climate change, it is crucial to develop strategies and integrate diverse knowledge to enable architects to make informed decisions in the early stages of design. Transitioning to positive buildings requires a multidisciplinary approach, integrating various scientific disciplines in architectural design. This research evaluates cladding systems as passive design strategies to reduce environmental impacts and achieve LEED certification during the operational phase of buildings. Focusing on a large office building in Boston, the study assesses three types of cladding—aluminum, polycarbonate, and a hybrid system—examining their roles in energy consumption, Annual Sunlight Exposure (ASE < 10%), and Spatial Daylight Autonomy (sDA > 50%). The research offers a comprehensive analysis using advanced parametric tools like Rhino Grasshopper for modeling, Honeybee and Ladybug for climatic analysis, OpenLCA for environmental impact assessments, Wallacei for optimization, and Design Explorer for model selection. Initial findings indicate that aluminum cladding is thermally favorable but does not meet LEED sDA standards. Polycarbonate cladding meets sDA levels but fails ASE criteria. To address these deficiencies, a hybrid system was optimized using the NSGA-2 algorithm and Wallacei selection methods, meeting both sDA and ASE criteria and demonstrating enhanced sustainability. This system, comprising approximately 93.18% aluminum and 6.82% polycarbonate, optimizes daylight autonomy and minimizes thermal gains and losses, with strategic skylight distribution—13.58% east, 7.72% south, and 10.96% west. The strategic use of advanced parametric and optimization software in this research empowers evidence-based decision-making in sustainable architecture, emphasizing the need for a holistic approach to achieve optimal outcomes.

Keywords: Passive Design, positive buildings, Cladding Systems, life cycle assessment of buildings, Daylight Utilization

B.2 Investigating the Effect of Geometry to Approach Positive Buildings (MED GREEN FORUM 7th edition 2024)

B.2.1 Abstract

As global imperatives for sustainability intensify, understanding the intricate connections between geometric design and the dual goals of energy efficiency and environmental responsibility becomes paramount. This research aims to systematically investigate the influence of architectural geometry on the creation of positive buildings, encompassing both positive energy and positive environmental impact structures.

The study employs a multidisciplinary approach, integrating architectural design principles with advanced simulation techniques to scrutinize the impact of various geometric configurations on the performance of buildings. Specifically, the research focuses on the positive energy aspects, exploring how geometry can optimize energy generation and consumption. Simultaneously, it delves into the environmental impact, examining how geometric considerations contribute to resource efficiency, reduced ecological footprint, and overall environmental harmony.

Through a comprehensive analysis of geometric parameters between three different forms, this research seeks to identify optimal design strategies that promote positive energy outcomes and environmental sustainability concurrently. To achieve this objective, a comprehensive inquiry into three parametric forms of dome space structure, flat roof, and barrel was conducted. The foundational stages involved architectural modeling and energy analysis through the utilization of Rhino software, complemented by the integration of Grasshopper, Honeybee, and Ladybug plugins. Structural assessments were subsequently performed using Karamba 3D, followed by a meticulous environmental impact analysis facilitated by One Click LCA. The findings of this investigation are anticipated to provide valuable insights for architects, designers, and policymakers involved in the creation of buildings that not only minimize their environmental impact but actively contribute to a positive, sustainable future.

This study contributes to the evolving discourse on positive buildings by bridging the gap between architectural design and environmental performance, fostering a holistic approach toward the development of structures that align with global sustainability goals, and uncovering the nuanced relationships between geometry and environmental impact. It seeks to provide actionable insights for architects, designers, and policymakers involved in sustainable building practices. The findings contribute to the development of design guidelines that prioritize environmentally responsible choices, fostering a paradigm shift toward the creation of buildings that actively promote ecological balance. Ultimately, this study contributes to the ongoing dialogue on sustainable architecture, offering practical considerations for mitigating environmental impact through thoughtful geometric design.

Keywords: Architectural Geometry; Positive buildings; Sustainability Imperatives; Optimal Design Strategies; Environmental Impact Analysis

B.3 Explaining Positive Building definition: A Review and Revision (MED GREEN FORUM 7th edition 2024)

B.3.1 Abstract

To achieve a carbon dioxide (CO_2)-free and energy-neutral environment by the year 2050, a unified global commitment is imperative. While current strategies predominantly emphasize improving energy efficiency and decarbonizing structures, effectively realizing climate change mitigation goals requires the formulation of a comprehensive agenda. Infect to achieve climate change mitigation goals, it is critical to consider not just preserving but also regenerating the world's severely devastated ecosystems and human populations. Going beyond the paradigm of high-efficiency building is essential for preserving and regenerating environmentally compromised ecosystems and human populations. The conceptualization of edifices characterized by positive impact and positive energy is pivotal in facilitating the transition towards a low-carbon global milieu.This study critically examines the discourse on Positive Environmental Buildings (PEB) and Positive Impact Buildings (PIB) through a comprehensive review of contemporary literature on environmental building paradigms, with a focus on works published after 2000, identified through Scopus and Google Scholar. The research adopts a dual-phase methodology, starting with the refinement of search parameters and the enhancement of the research strategy, and culminating in the extraction of pertinent data. The investigation meticulously explores concepts, definitions, and parameters of various environmental building design approaches. Following a meticulous examination of methodologies and objectives, the present study posits a descriptive framework and schematic for positive building design, derived from the discerned outcomes of the investigation. The delineated framework incorporates innovative strategies that transcend the confines of mere energy efficiency, encompassing a holistic consideration of the broader positive impact on both the environment and human well-being. This entails a pronounced emphasis on the integration of cutting-edge technologies, utilization of sustainable materials, and active engagement with local communities to foster the development of buildings that not only adhere to but also promote environmentally regenerative principles within their respective ecosystems.in conclusion this research significantly contributes to the ongoing discourse surrounding environmental building paradigms by advancing the conceptualization of Positive Environmental Buildings and Positive Impact Buildings. By proffering a comprehensive framework for positive building design, the study furnishes a practical guide for architects, policymakers, and stakeholders, delineating avenues through which they can meaningfully contribute to the global transition towards a sustainable and low-carbon future.

Keywords: Positive buildings; sustainable architecture; green building; regenerative design; Zero Carbon emissions Buildings

B.4 A Review of Sustainable Pathways to Climate-Neutral Buildings: Technological Synergy of Advanced Cladding Systems and Building Integrated Photovoltaics (NMP 2024)

B.4.1 Abstract

This literature review succinctly evaluates the integration of building-integrated photovoltaics (BIPV) within advanced cladding systems, focusing on their role in achieving climate-neutral buildings. It investigates the technological synergy between these systems, underscoring their potential to foster sustainable architectural practices. The methodology involves a systematic review of literature from 2010 to 2024, sourced from Google Scholar, SpringerLink, and ScienceDirect. This structured approach enables a comprehensive assessment of the advancements and challenges in integrating cladding systems with photovoltaics. By methodically pairing articles on cladding materials and photovoltaic technology, we extract insights into their combined efficiency, aesthetic integration, and environmental sustainability. By doing a review of research this study highlights key technological aspects that make these integrated systems conducive to climate neutrality, particularly their capability to reduce energy consumption and carbon footprint. We anticipate that the findings will illuminate the benefits of this synergy, projecting enhanced performance and environmental advantages. Expected outcomes of this research will contribute to the evolving dialogue on sustainable building technologies. Our aim is to establish a clear understanding of how combining advanced cladding systems with photovoltaics paves the way for innovative, climate-positive building solutions. The results are intended to inform future research and practical applications, steering the architectural field towards climate-neutral objectives.

Keywords: Building Integrated Photovoltaics (BIPV), Sustainable Cladding Systems, Climate-Neutral Architecture

B.5 Process Management of Spatial Structures to Address Positive Buildings with the Goals of Sustainable Development (MED GREEN FORUM 6th edition 2022)

B.5.1 Abstract

In the latest years, the main issues facing the world are environmental challenges such as global warming, ozone depletion, and destruction of natural habitats. Therefore, there is an emergent need for worldwide commitment to prevent and reduce environmental pollution. In this context, spatial structures play an important role in reducing environmental pollution, especially in large projects, because they use new technologies, lightweight constructions and materials, prefabricated systems, scientific and applied concepts in design and execution while observing seismic safety requirements that are related to the structure durability and stability.

The aim of this research is to define parameters evaluating the contribution and limitation of strategies by defining a managerial view of the spatial structure process to optimize energy consumption, pointing out the climatic design as a solution to improve the efficiency as structures with the potential for positive buildings.

The research process of Architecture, Engineering, and Construction (AEC) in spatial structures is examined in four categories: Design; Construction; Carrying; Assembly, and Installation. After introducing each category, the goals and results obtained from the effects of climatic design are discussed, and, finally, according to these results, an integrated management diagram to optimize energy consumption and to address positive buildings is presented.

This diagram is designed around a systematic axis, and it manages the optimal time, cost, and energy while considering the sustainability to develop a decision model and to strategically adopt a spatial structure as a prefabricated and engineered system in the design and construction planning of green facilities. The diagram is divided into four stages: Step1- Metric Determination for Positive Design; Step2-Integrate Axiomatic Design and Detailing; Step3-Integrate Design Knowledge and Environmental impact to develop the concept considering climatic potential; Step4-Result Verification by using software tools.

Keywords: Positive Buildings, Process of spatial structures, Spatial Structures, Sustainable developments

B.6 Investigating the effect of form and material of space structures on energy consumption in hot and dry climates Case study: Kerman city (NMP,2022)

B.6.1 Abstract

Climate and environmental conditions have a special and inevitable physical and psychological effect on humans that should be considered in the design of buildings depending on the heating or cooling situation. Climate design is a way to achieve bioclimatic comfort. The basic solutions to bioclimatic design are commonly found in vernacular buildings. Some modifications and improvements can be also observed while particular methods differ depending on the regional traditions, available materials, developed techniques, etc. The building's outer skin is the interface between the interior and exterior. The complex design of the skin can bring the issue of energy consumption optimization closer to the ambitious goals of energy saving through environmental considerations. An important function of the outer skin of the building (decking of space frames) is to control environmental and physical factors such as light, heat, sound, etc. to achieve comfortable conditions with minimal energy consumption. Various simulation programs have been developed for this purpose that can lead the design solutions to the optimization of the building by simulating the building and measuring the exact energy consumption In this research, after researching and studying articles and researches in the field of comparing energy simulation software, it has been tried to use the latest and most-up-to-date simulation software.

Keywords: hot and dry climate, climate design, spatial structure's cladding, energy consumption, Kerman

B.7 Climatic Design Solution in Iranian Traditional Architecture to Provide Comfort Conditions

B.7.1 Abstract

One of the main issues facing the world is environmental challenges such as global warming, ozone depletion, and the destruction of natural habitats. The building sector has several direct and indirect effects on the environment. Construction not only consumes resources such as energy and raw materials but also generates waste and destructive air pollutants; This clearly shows that addressing the environmental problems caused by building and construction is very important and should be prioritized.

on the other hand, one of the most important ways to reduce environmental pollution is paying attention to energy efficiency and the use of passive systems to provide environmental comfort. investigating an efficient solution to provide comfort conditions in the building sector can be a good way to address decreasing environmental pollution, And one of the efficient solutions for optimal energy consumption is climate design.

Among the prominent examples of climatic design that have been able to optimal use of all types of energy and have used climatic solutions to meet the comfort needs of residents, we can mention the traditional Architecture of Iran, which, although it has different variations in climate, in practice, every area has been prevented from wasting energy to a great extent with special solutions and has provided comfortable conditions for users.

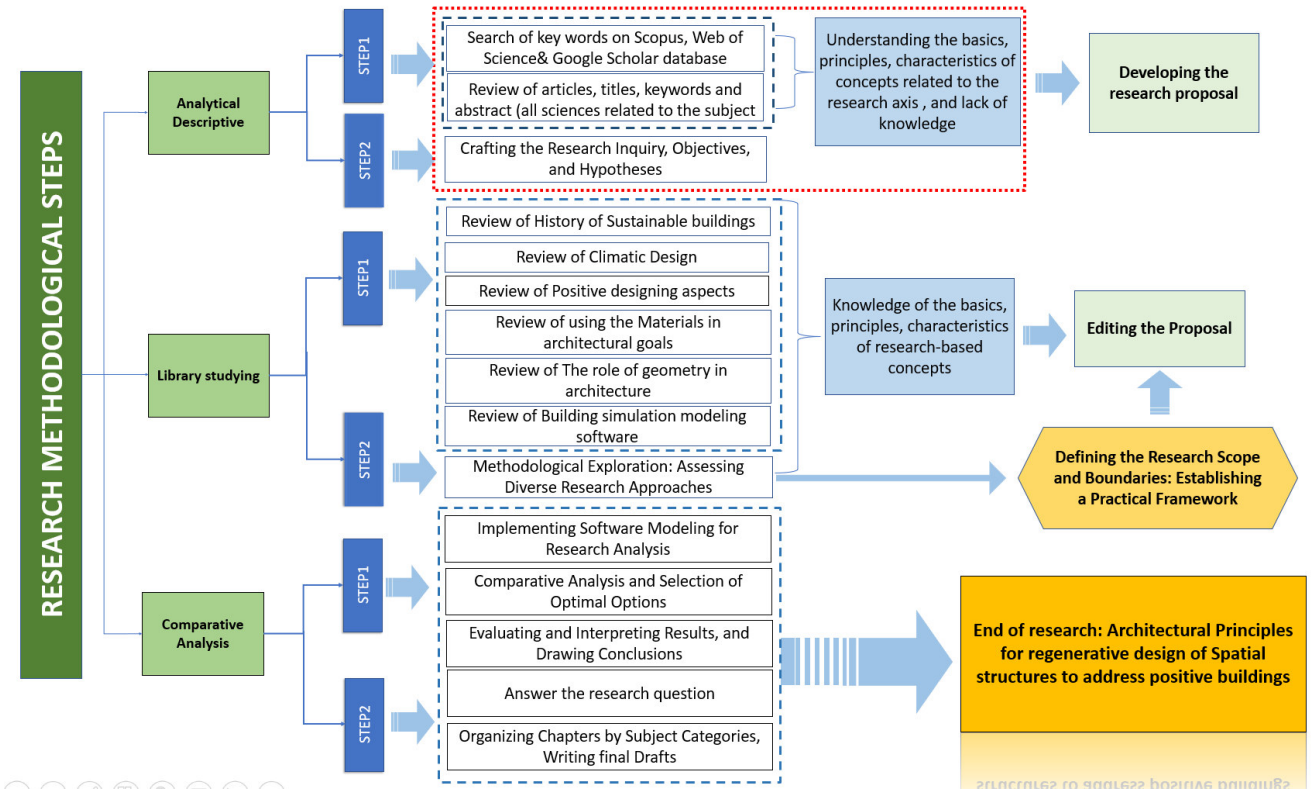
This article is a library study with an investigation and review of research done in the field of climate design and solutions for comfortable conditions. In order to familiarize ourselves with climatic traditional ways, After defining the climatic design and introducing the influencing factors in the making of a climate, the different climates of Iran have been introduced, and then by introducing the characteristics of hot and dry climates as a case study, The different elements of the traditional house have been introduced, then the climatic solutions used in the traditional houses of Iran to provide comfortable conditions for the users, have been analyzed and investigated.

Keywords: Climatic design, Comfort conditions, Dry and hot Climate, sustainable architecture, Climatic elements, renewable energy

Appendix C

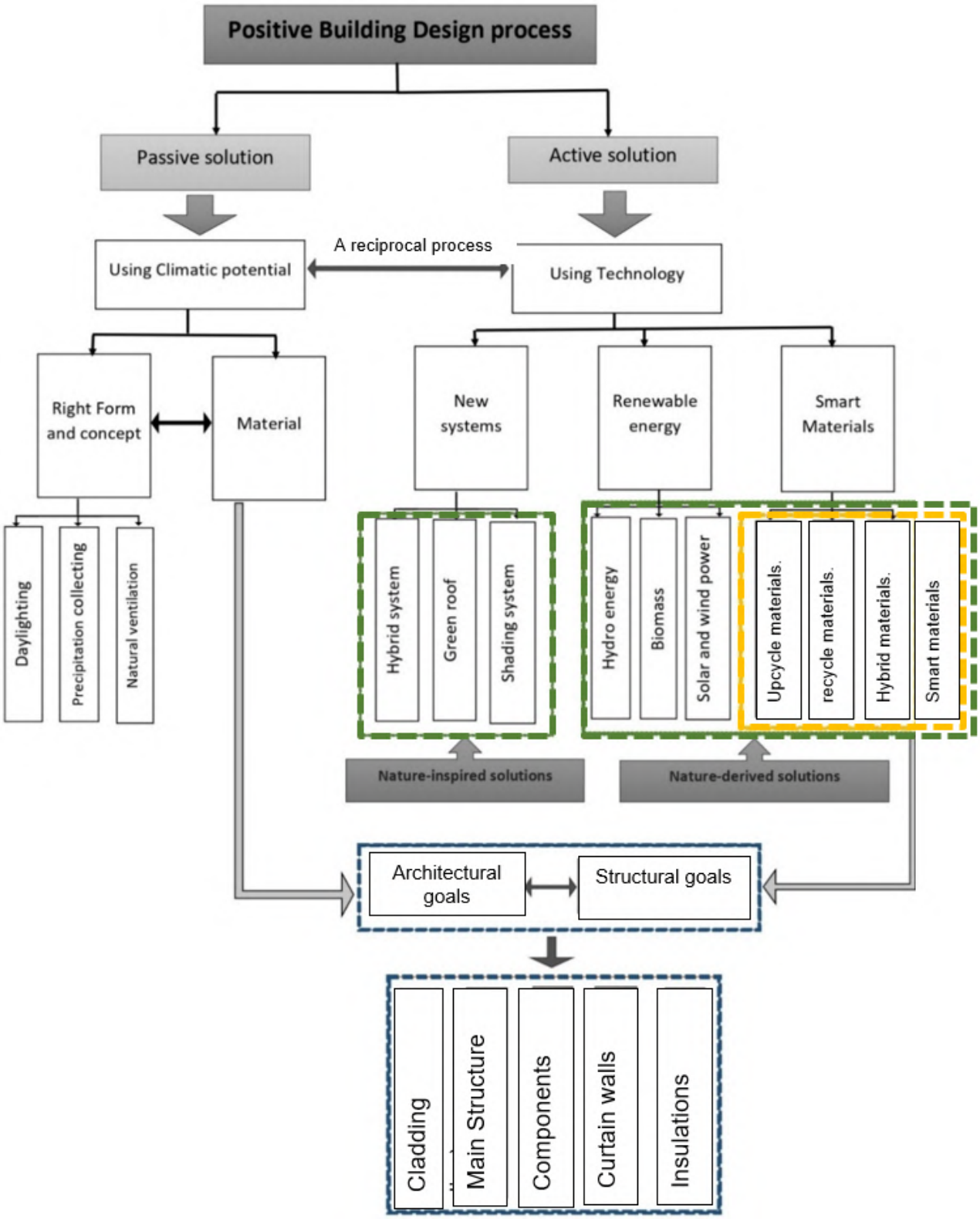
Chapter 1

Diagram 1.1: A summary of the General Research Method



Chapter 2

Diagram 2-1: Positive design Process (Reference: Author)



Chapter 3

Diagram 3.1 : Strategies for Regenerative Design

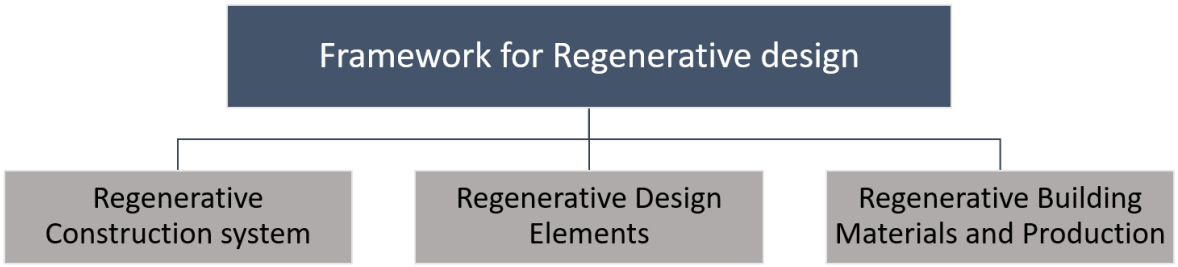


Diagram 3.2 : first framework for regenerative design

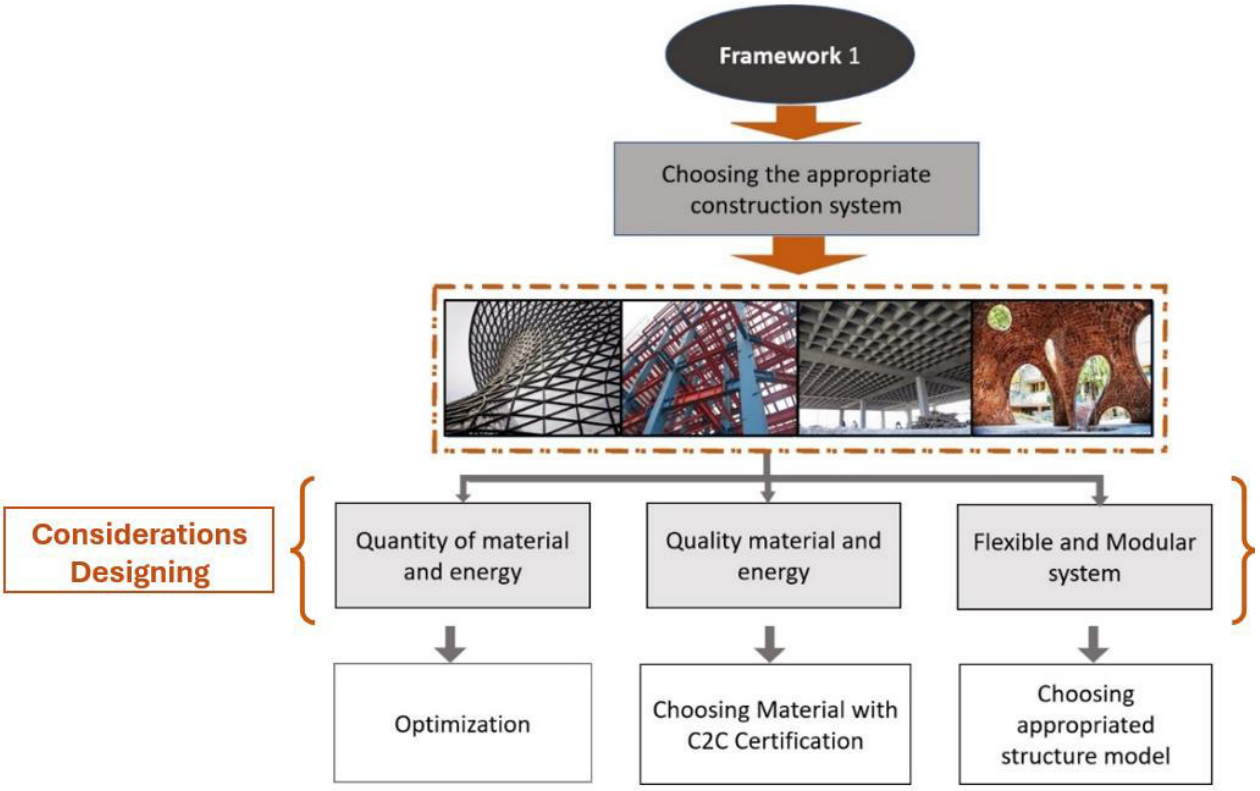
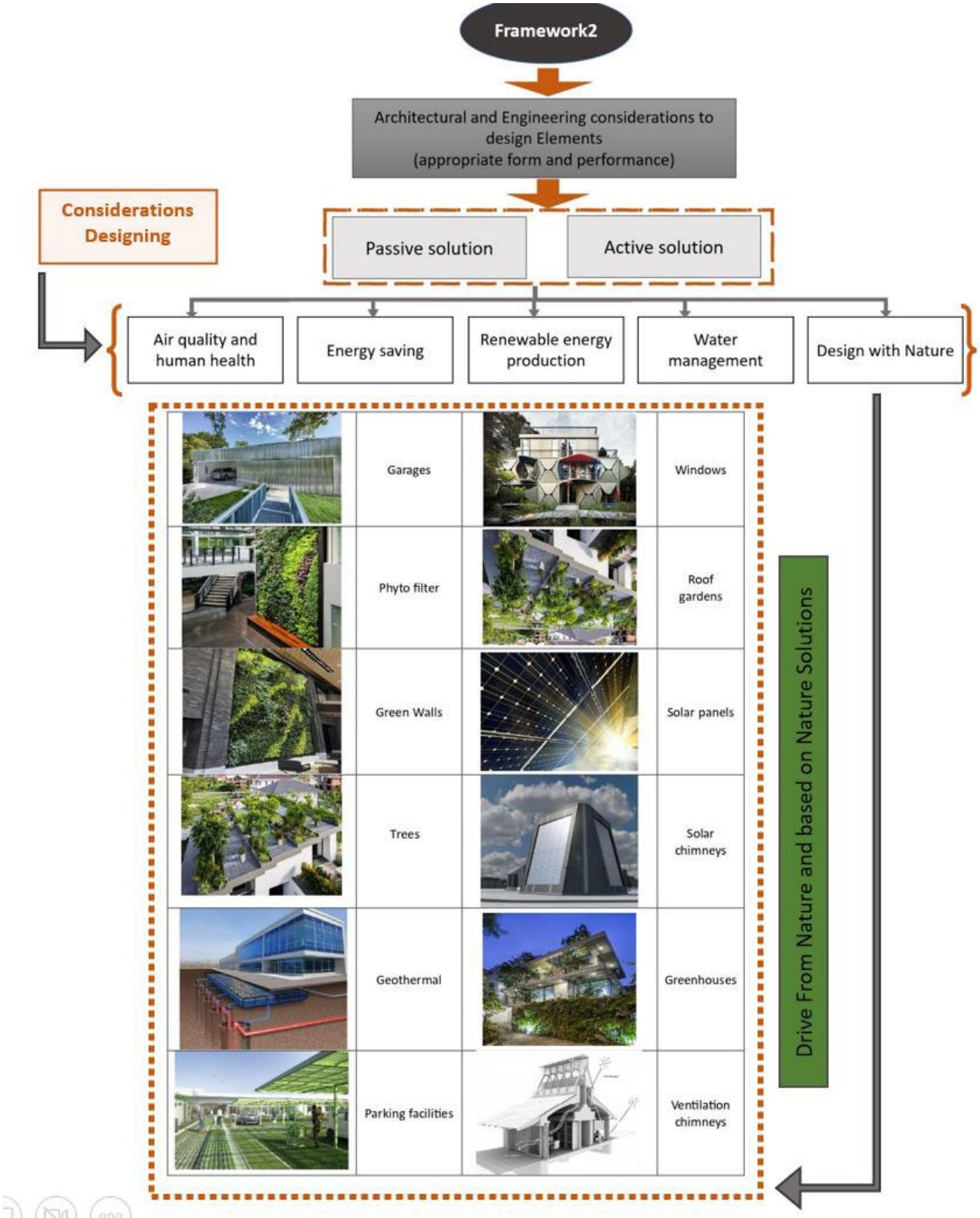


Diagram 3.3: second Framework for regenerative design (Photo's References:www.archdaily.com)



Chapter 4

Diagram 4-1: Methodological Process and Workflow

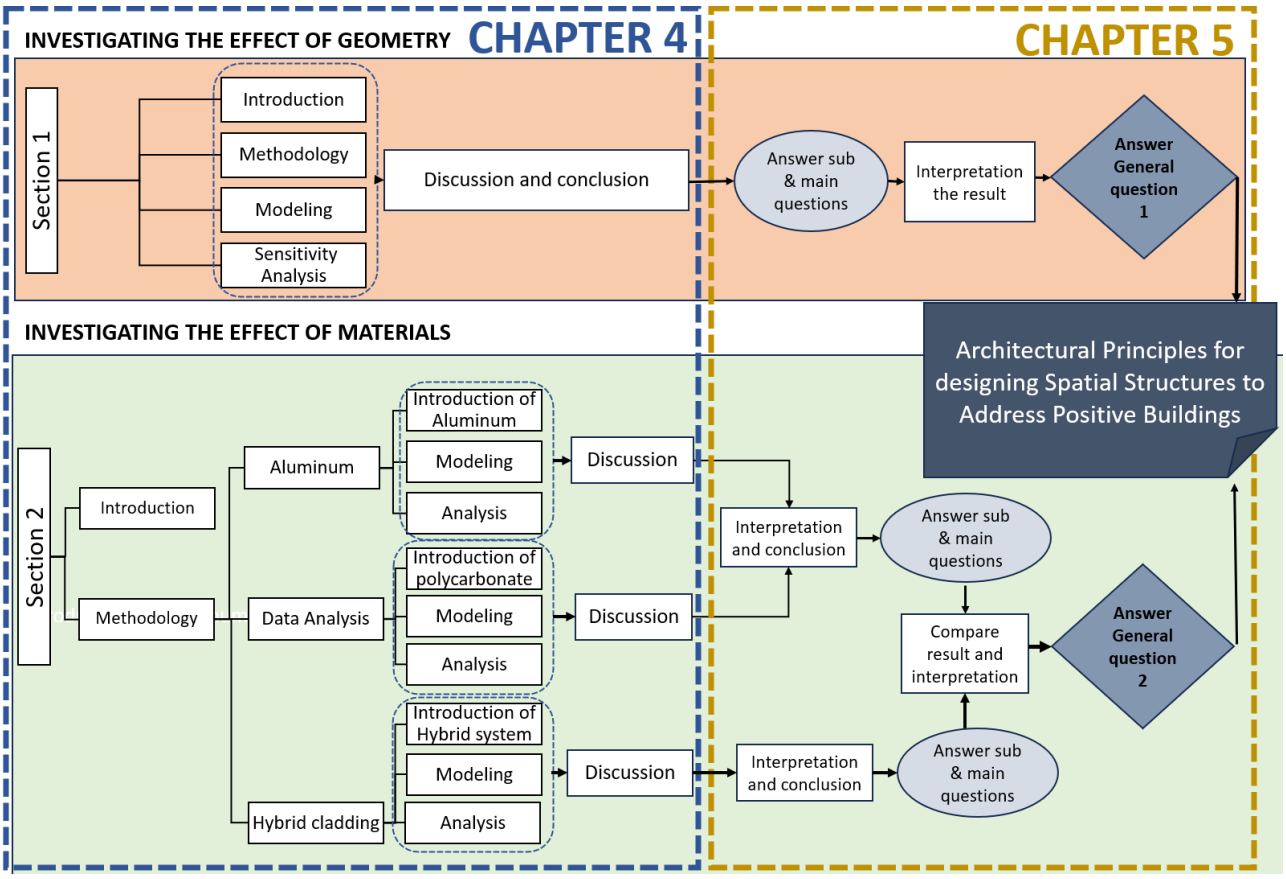
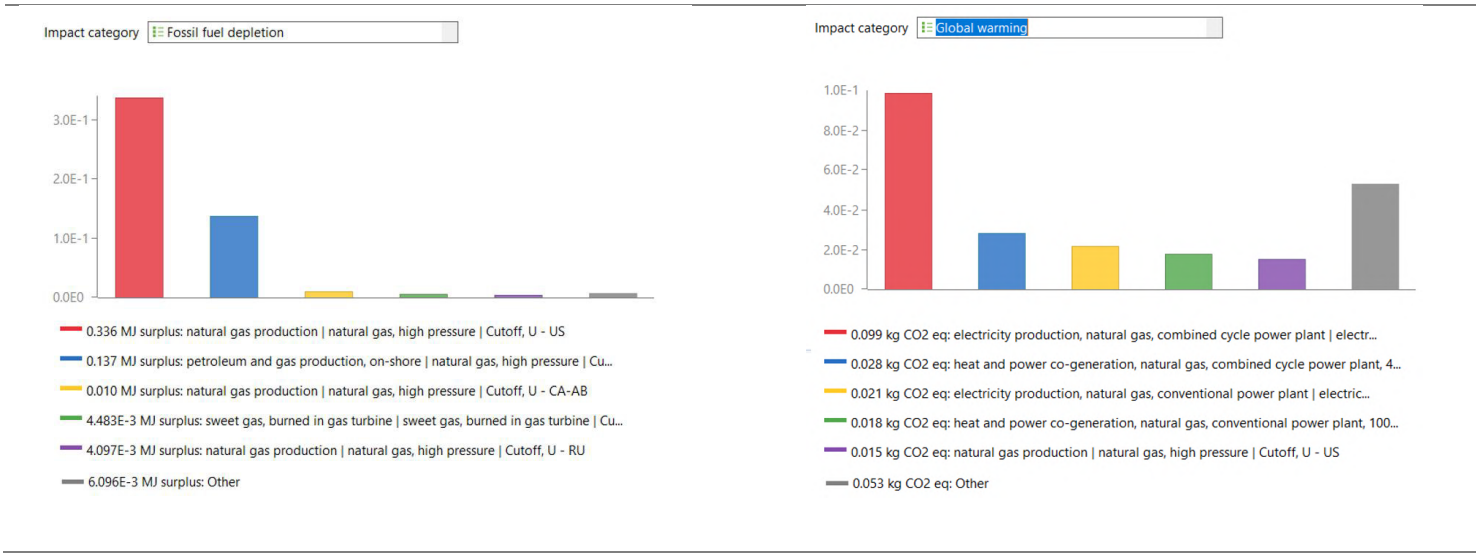
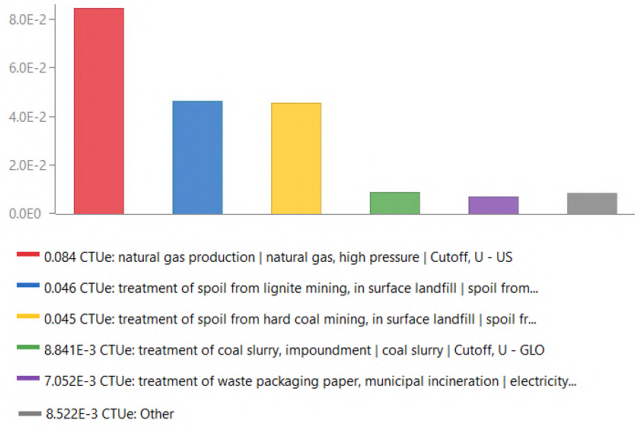


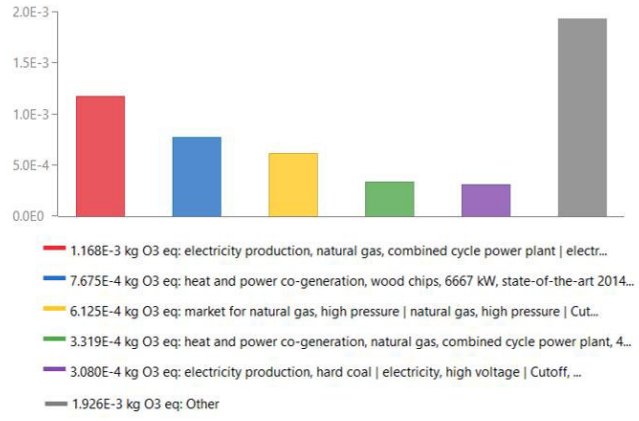
Diagram 4-2: The different flows contribution in per category



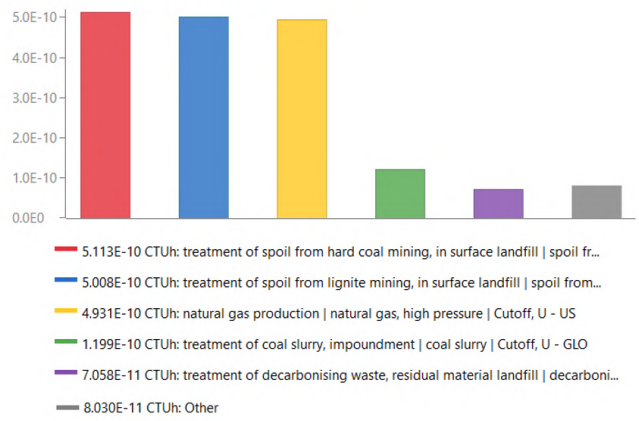
Impact category: Ecotoxicity



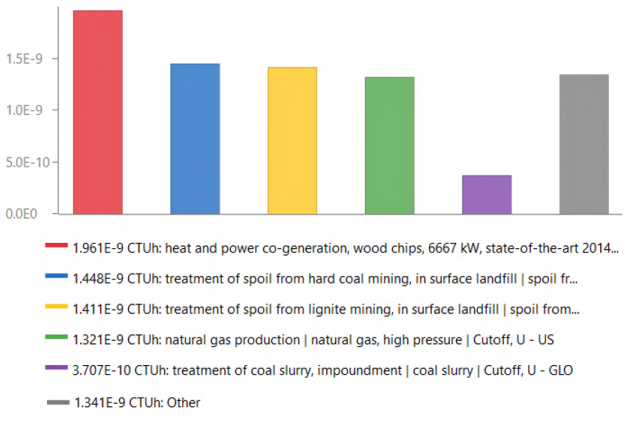
Impact category: Smog



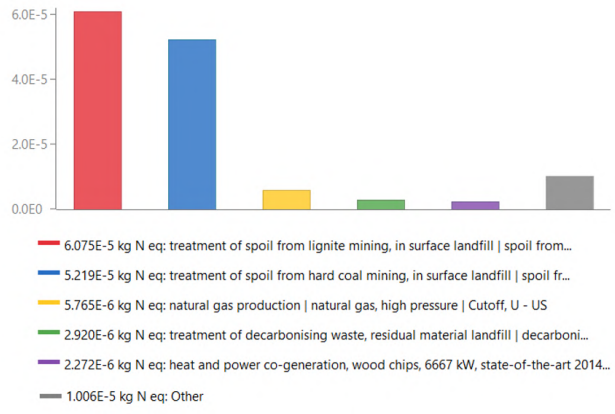
Impact category: Carcinogenics



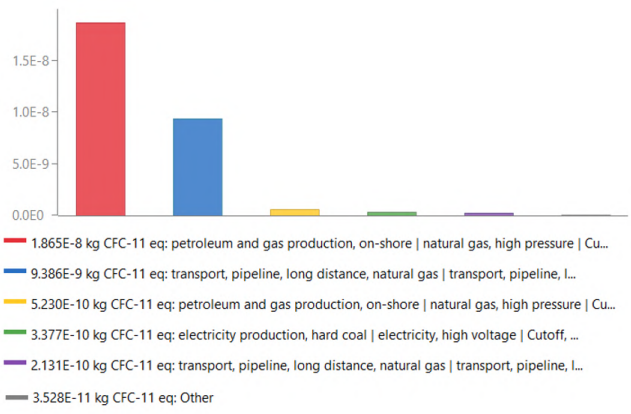
Impact category: Non carcinogenics



Impact category: Eutrophication



Impact category: Ozone depletion



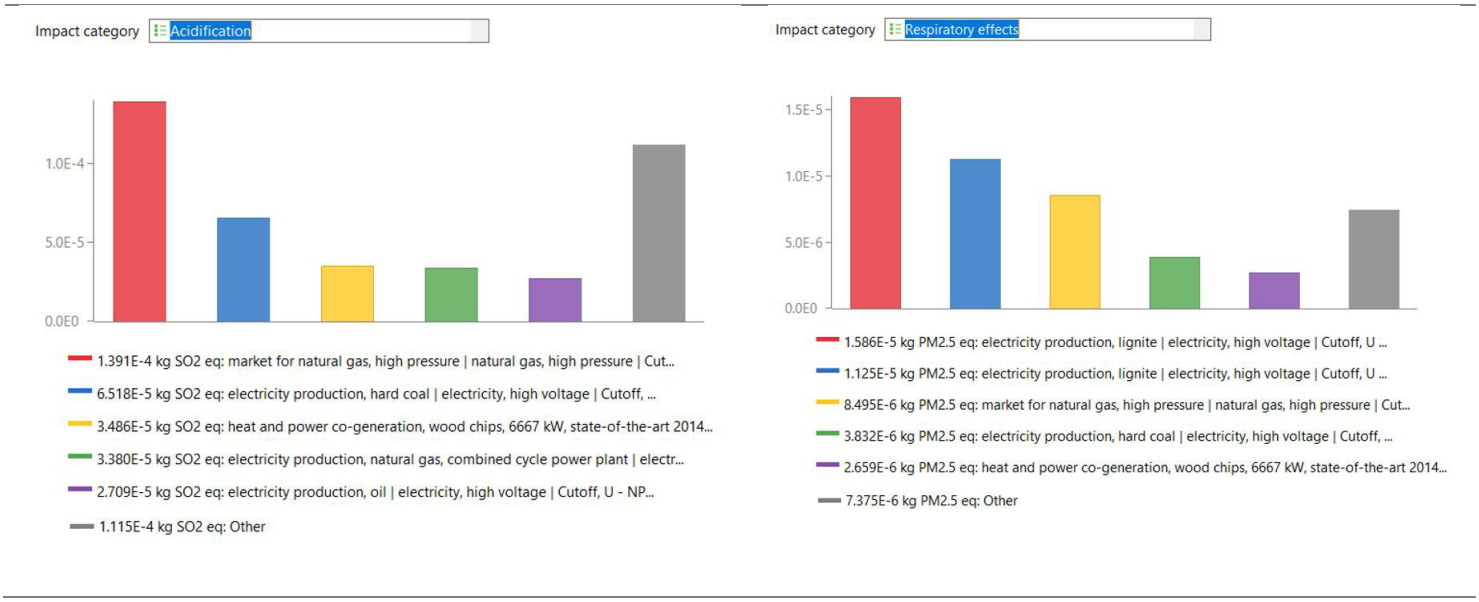
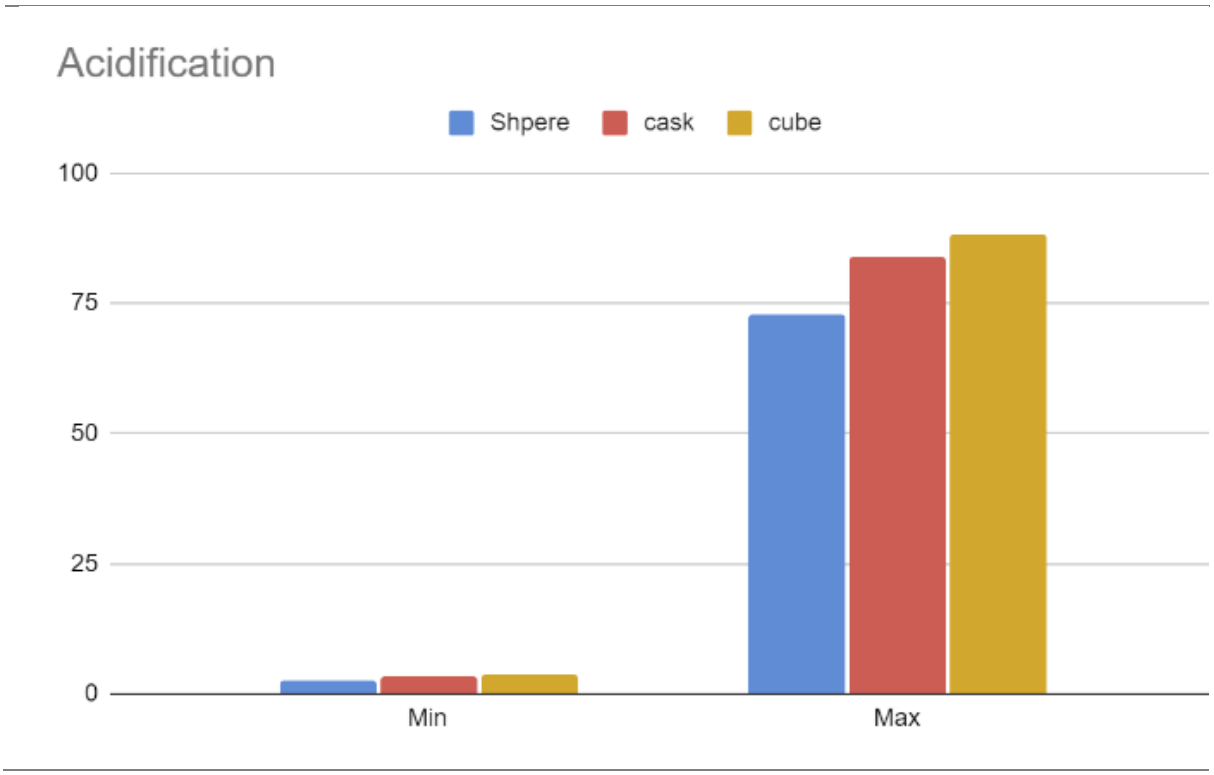
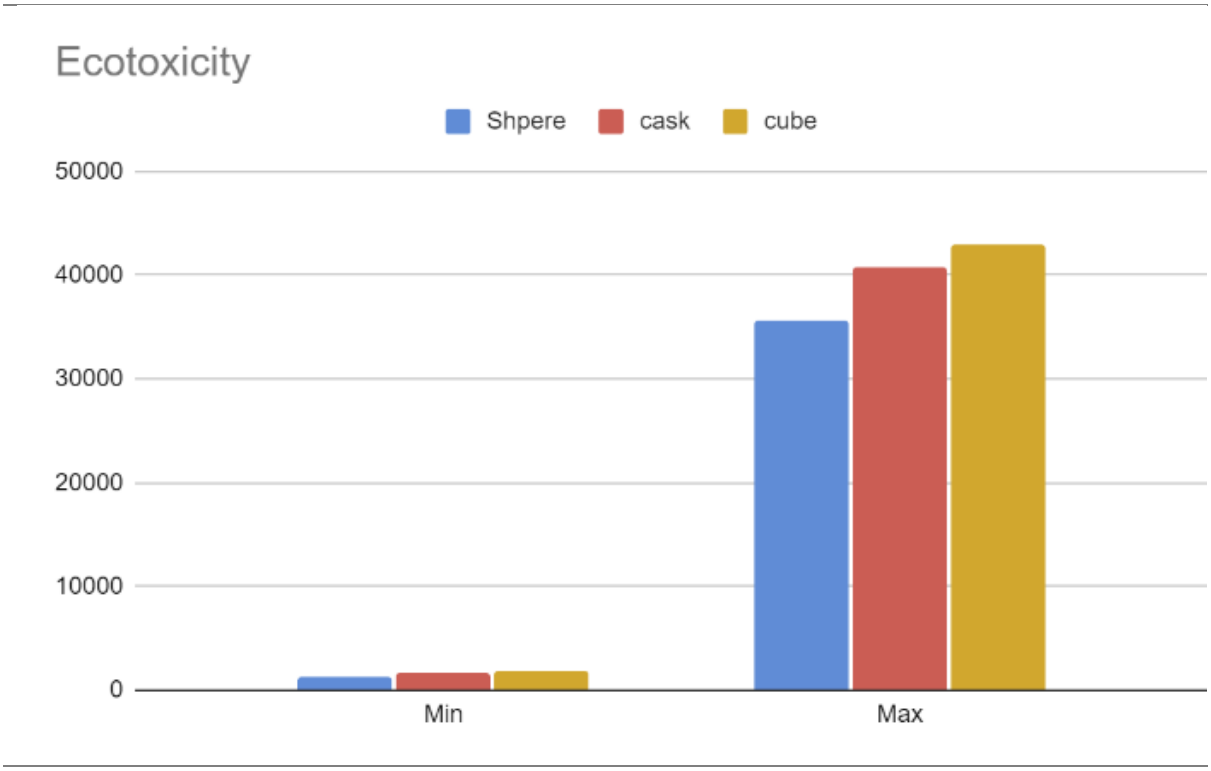
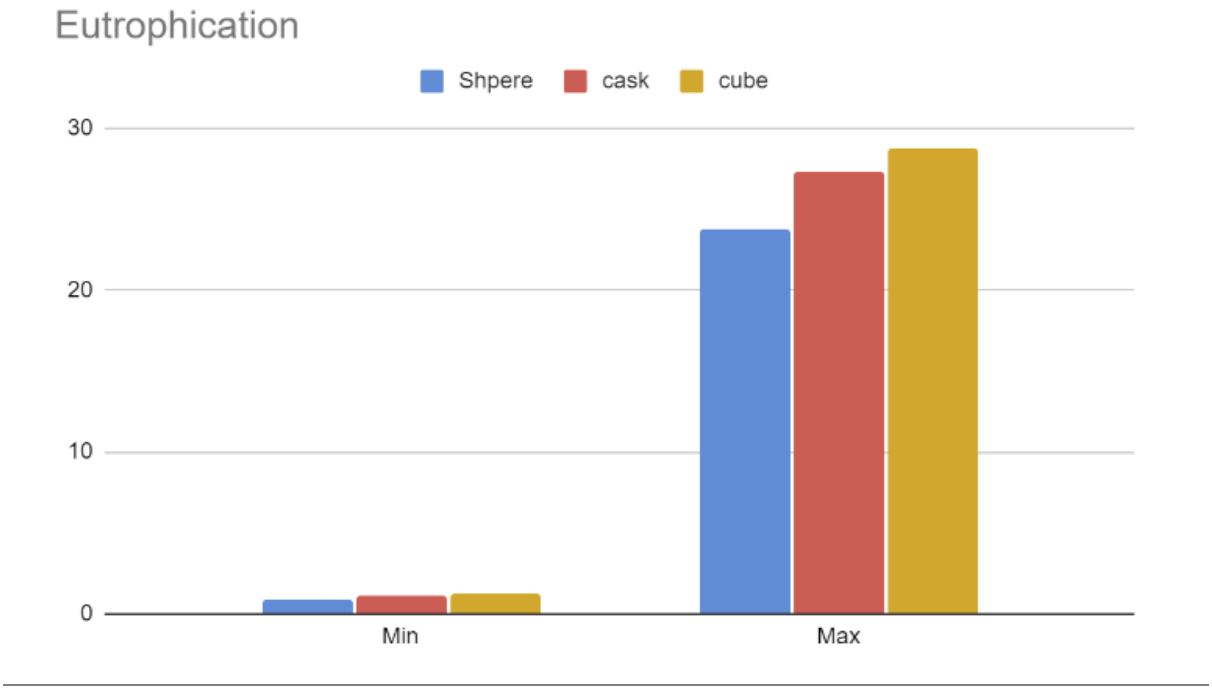
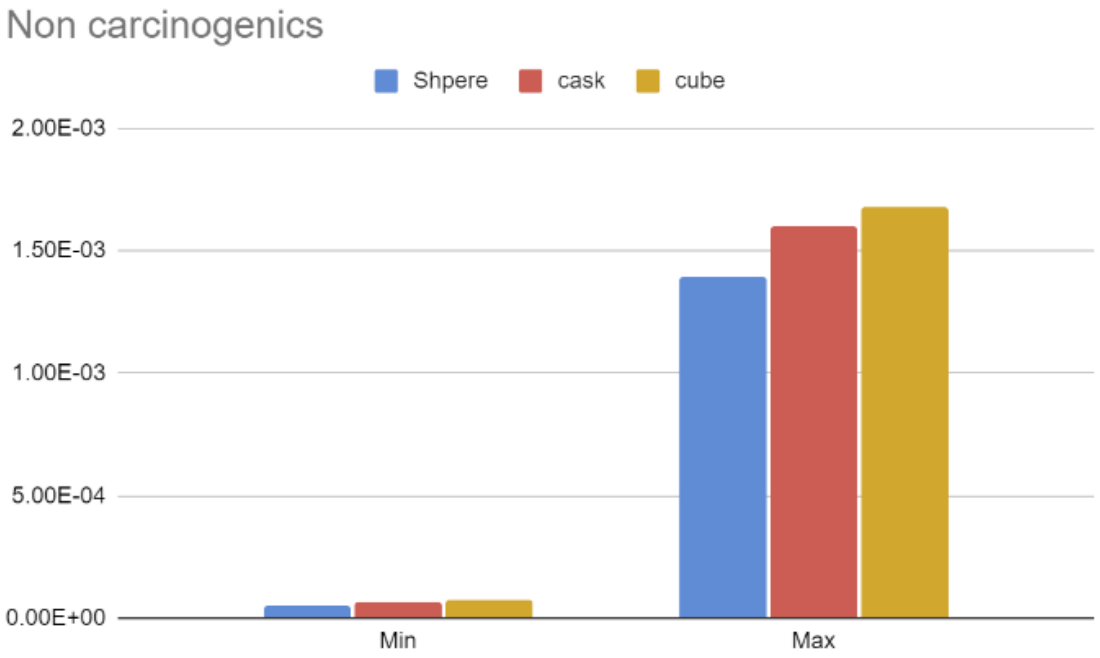


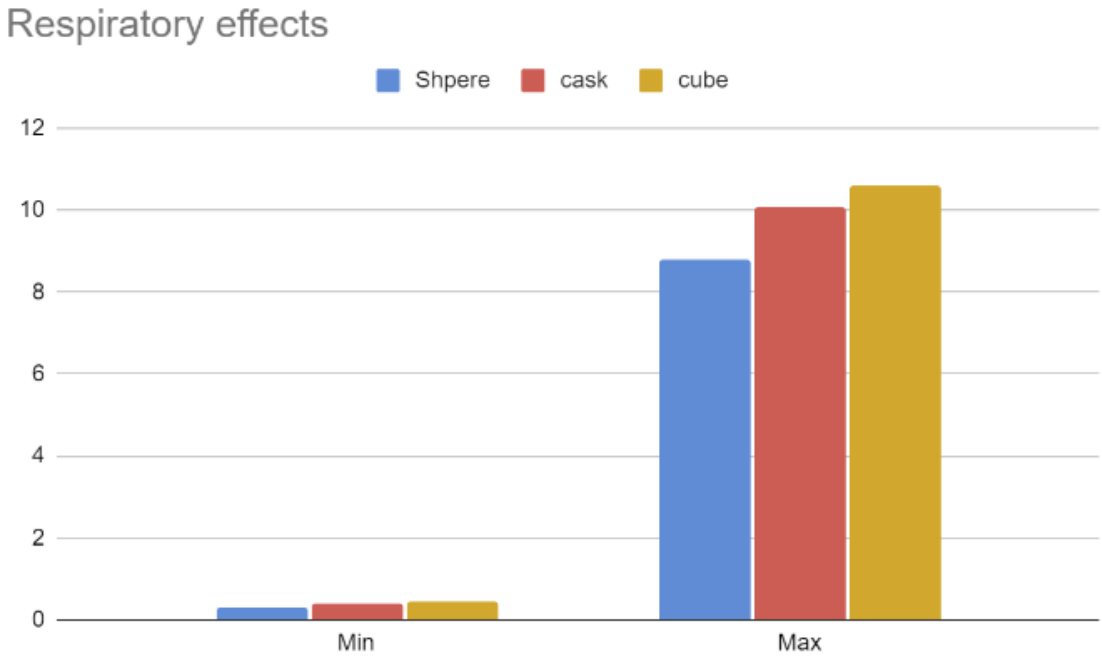
Diagram 4-3: comparison environmental impact pf different

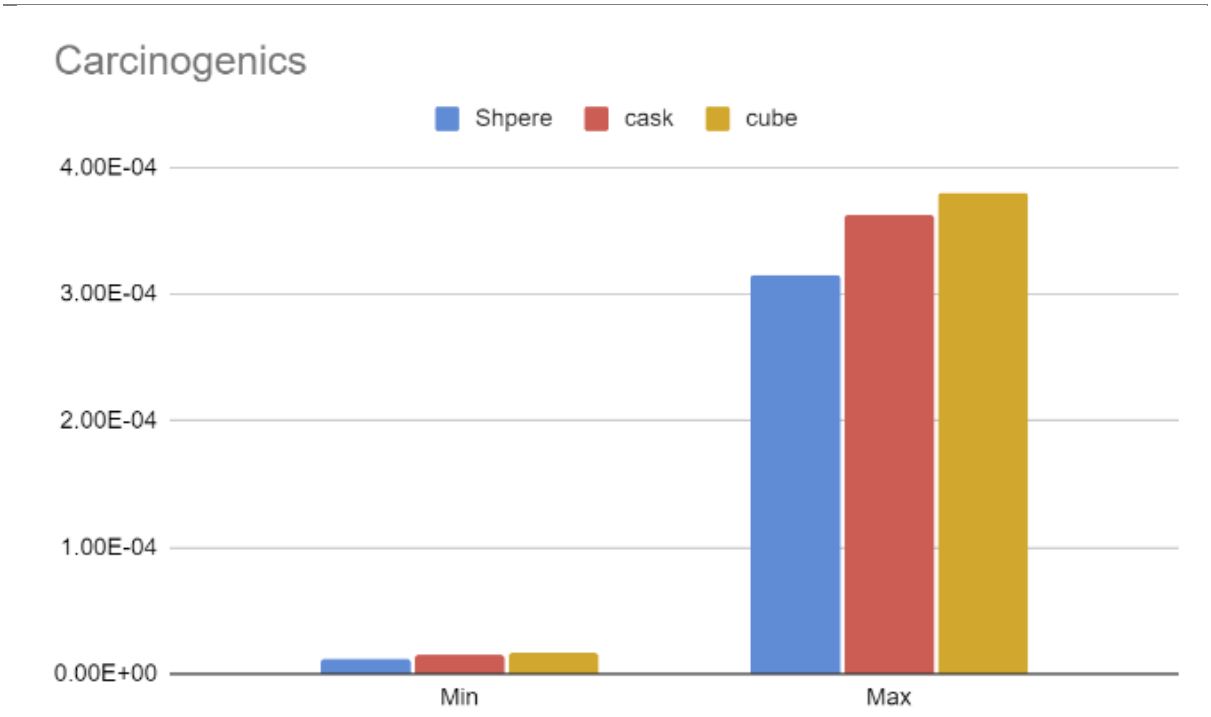


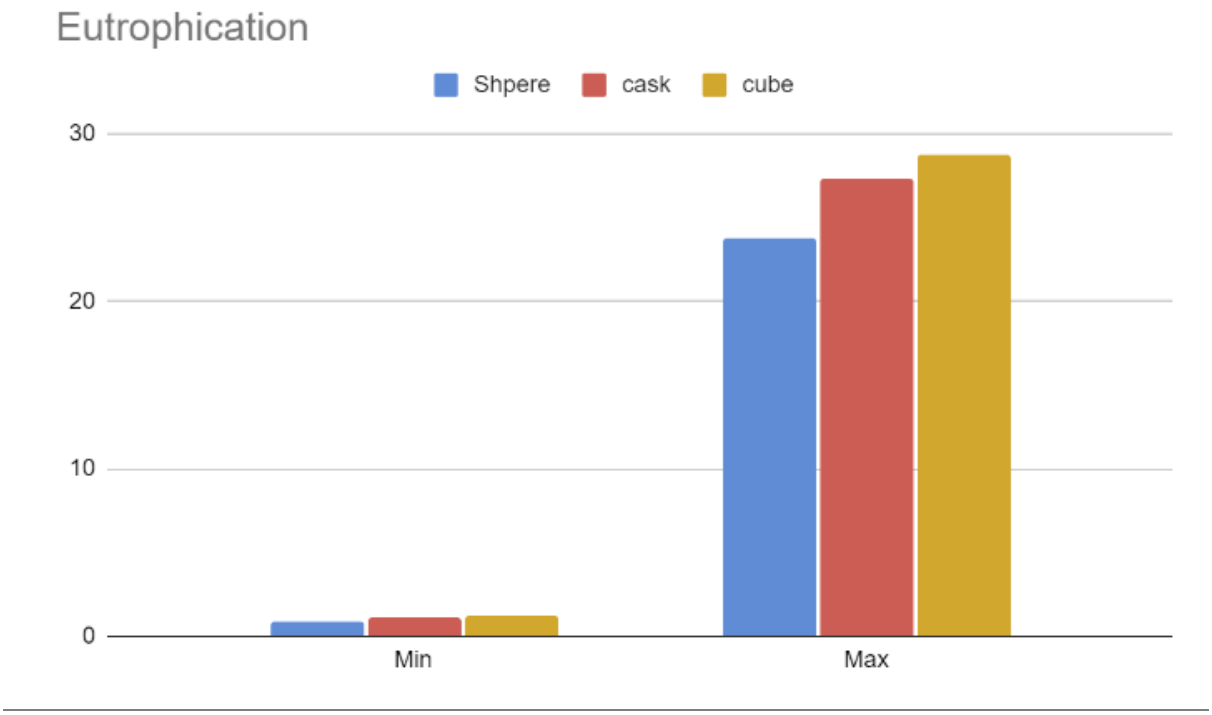

Ecotoxicity
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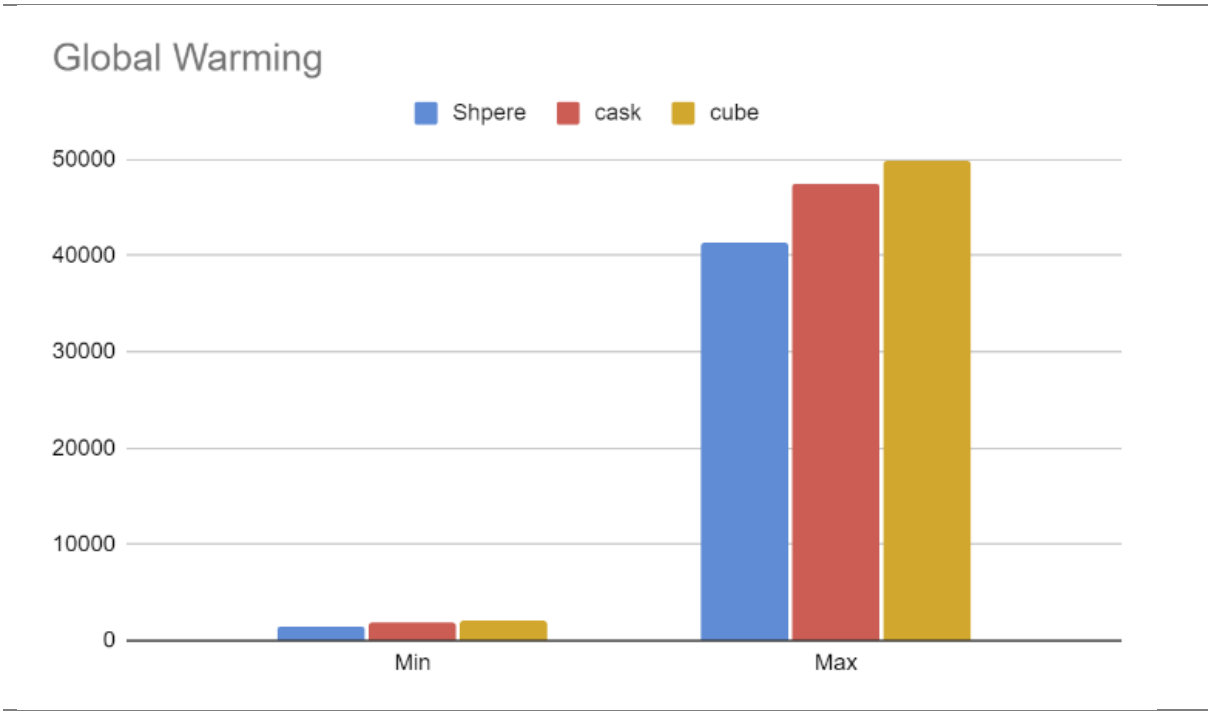

Eutrophication
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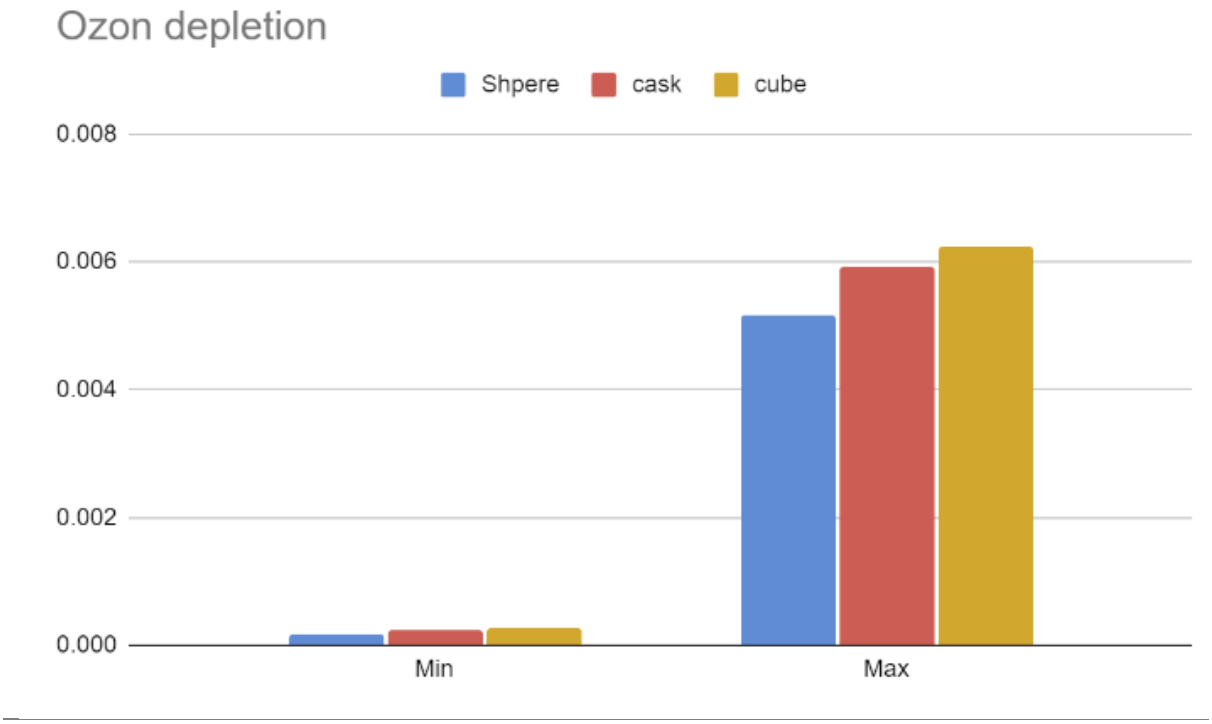

Non carcinogenics
Shpere
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2.00E-03
1.50E-03
1.00E-03
5.00E-04
0.00E+00
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Max


Respiratory effects
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cask
cube
12
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Min
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Carcinogenics
Shpere
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4.00E-04
3.00E-04
2.00E-04
1.00E-04
0.00E+00
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Eutrophication
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Global Warming
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Ozon depletion
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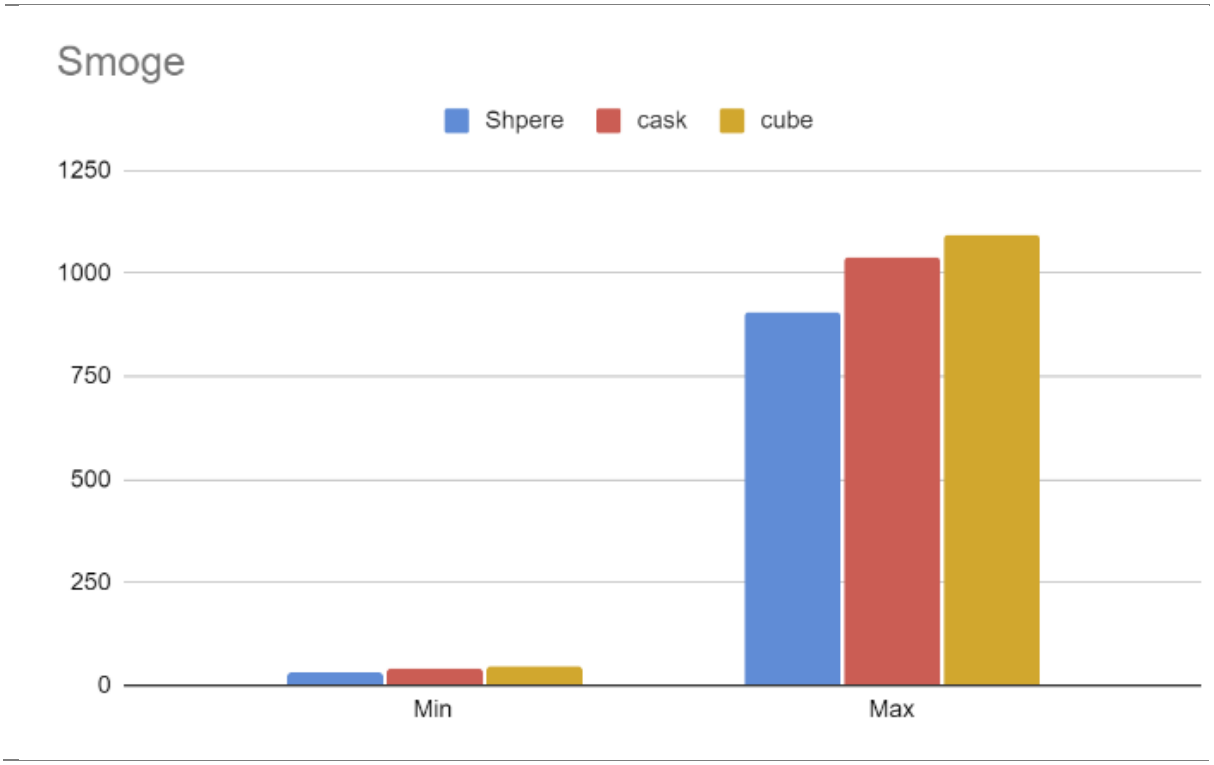


Diagram 4-4: Sphere Scotter plot

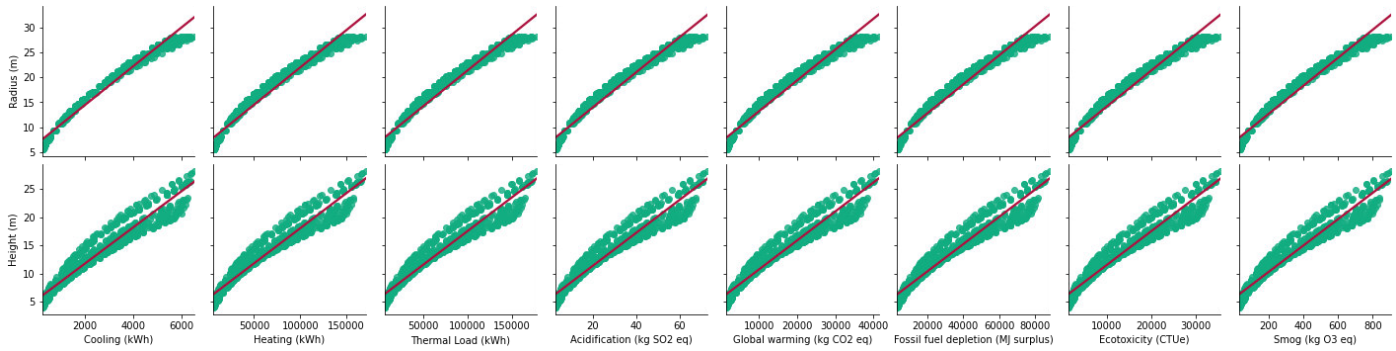
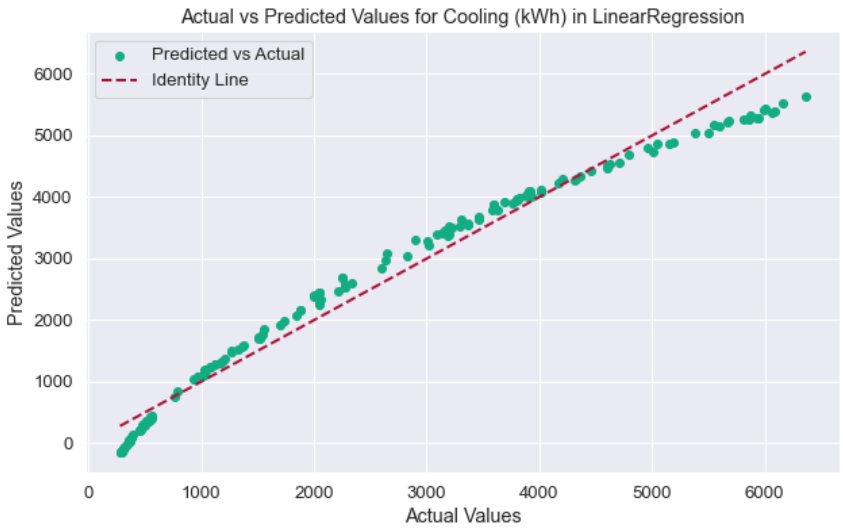
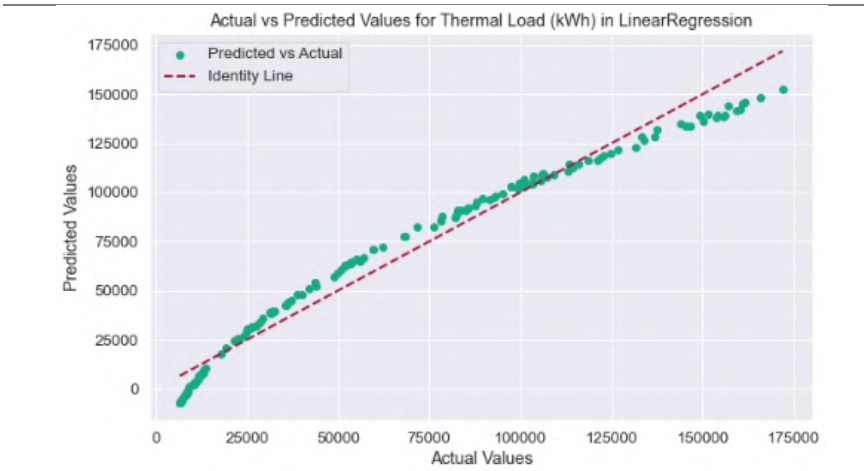


Diagram 4-5: Actual vs Predicted values for different outputs



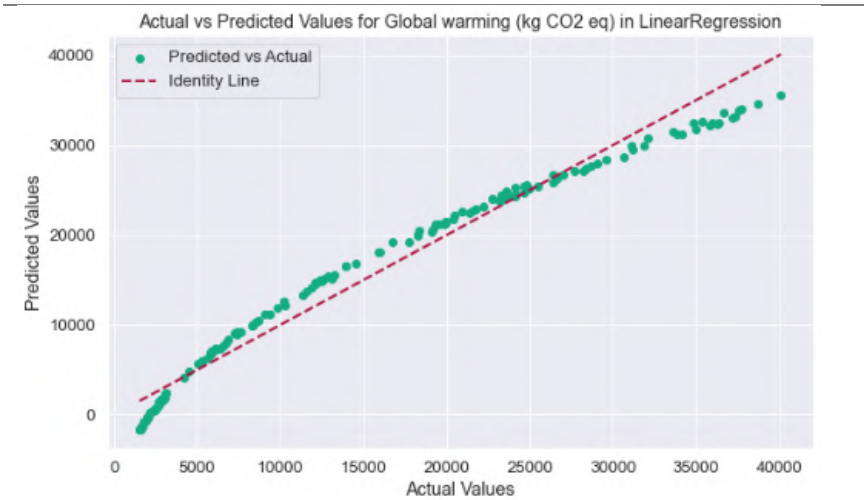
R-squared for Cooling (kWh): 0.9737

MSE for Cooling (kWh): 88315.59



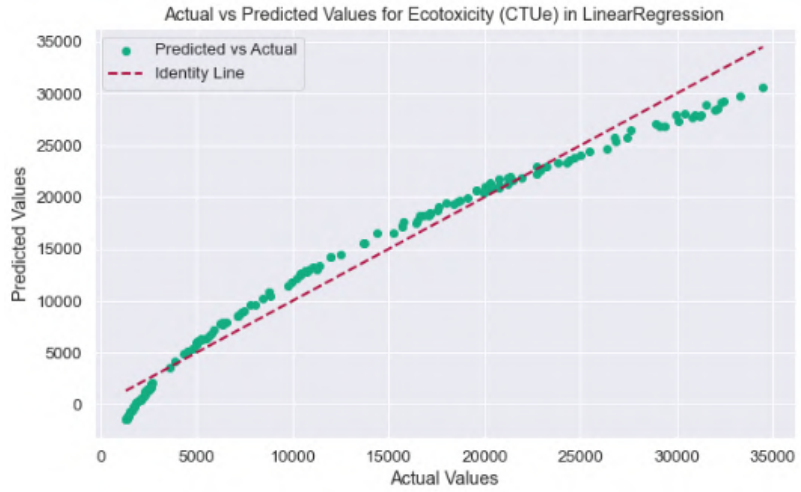
R-squared for Thermal Load (kWh): 0.9696

MSE for Thermal Load (kWh): 74501981.31



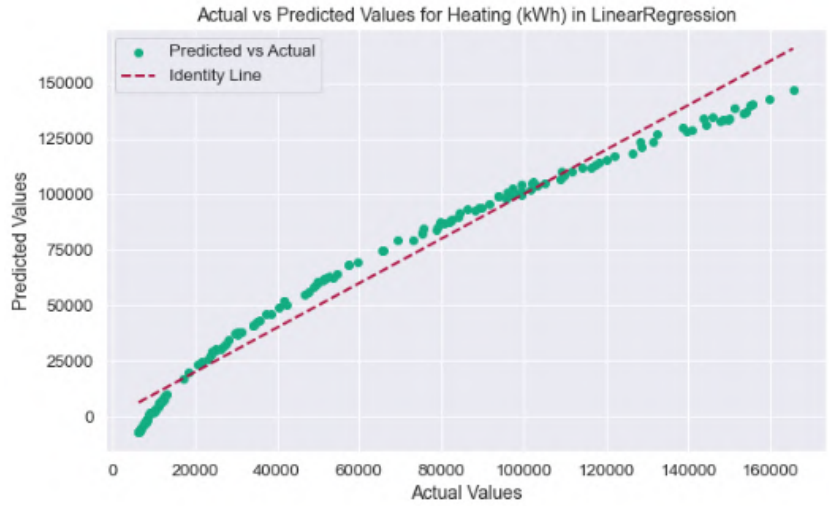
R-squared for Global warming (kg CO_2 eq): 0.9696

MSE for Global warming (kg CO_2 eq): 4052991.87



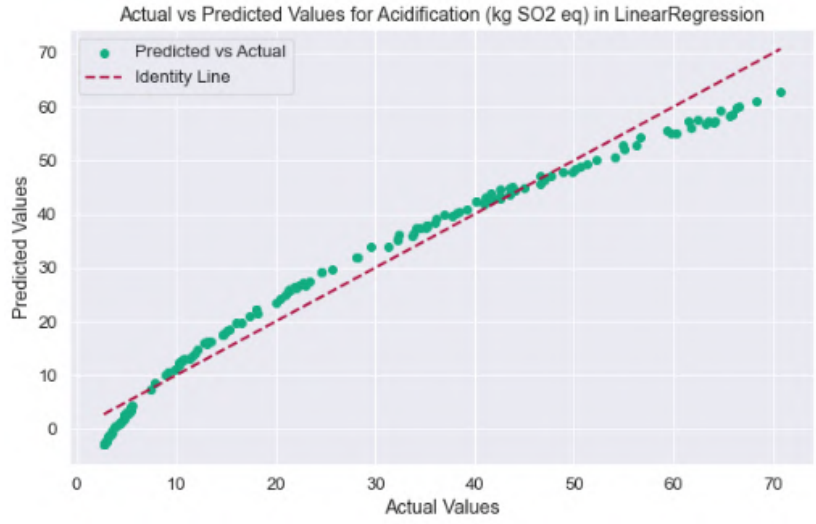
R-squared for Ecotoxicity (CTUe): 0.9696

MSE for Ecotoxicity (CTUe): 3000291.65



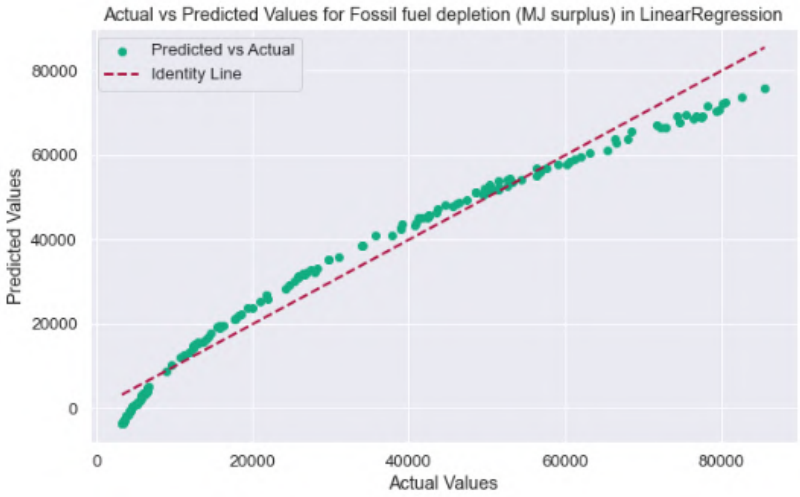
R-squared for Heating (kWh): 0.9694

MSE for Heating (kWh): 69531426.52



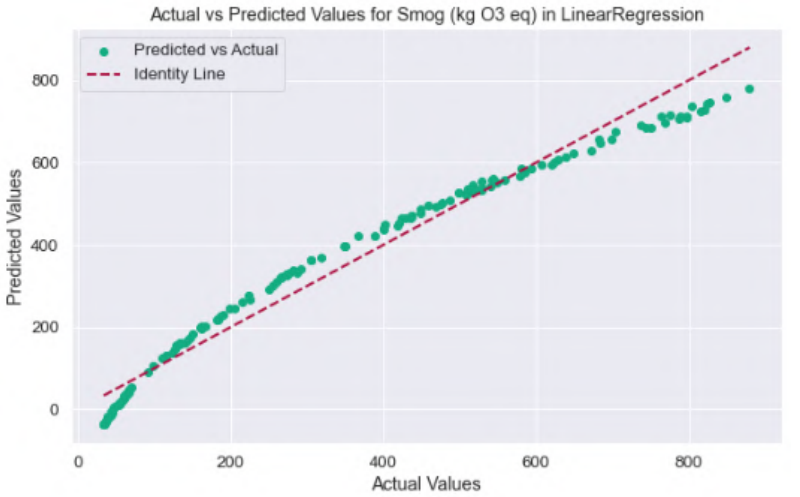
R-squared for Acidification (kg SO_2 eq): 0.9696

MSE for Acidification (kg SO_2 eq): 12.62



R-squared for Fossil fuel depletion (MJ surplus): 0.9696

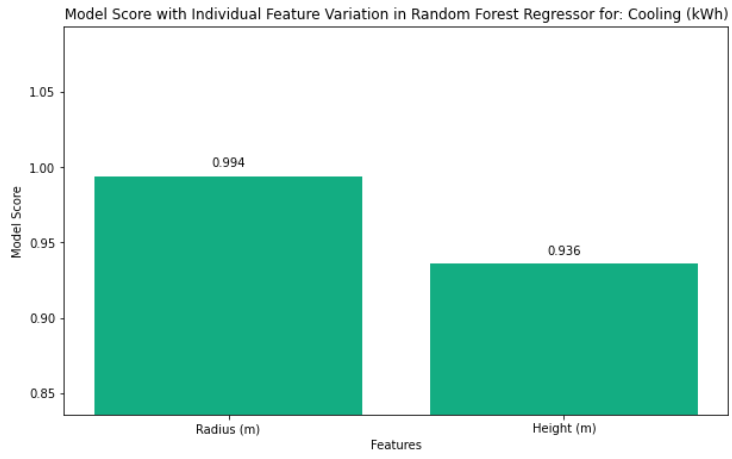
MSE for Fossil fuel depletion (MJ surplus): 18449748.01

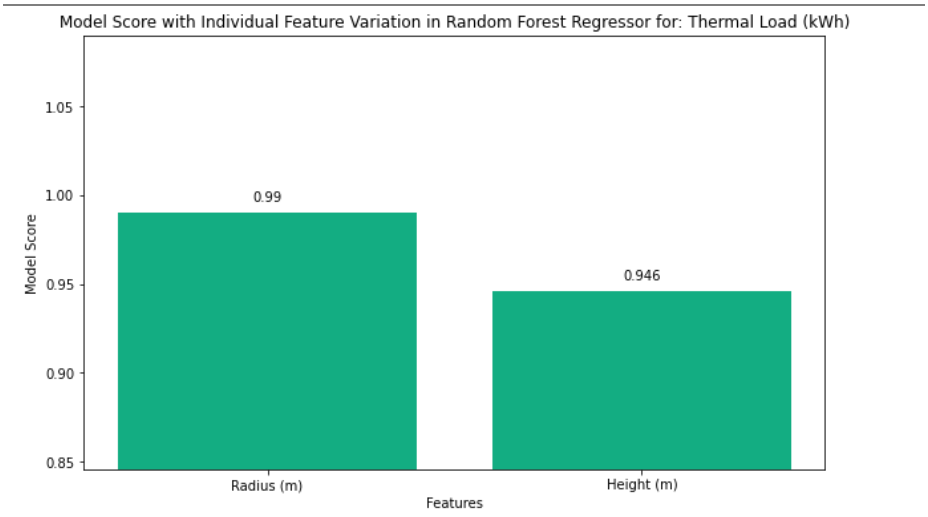


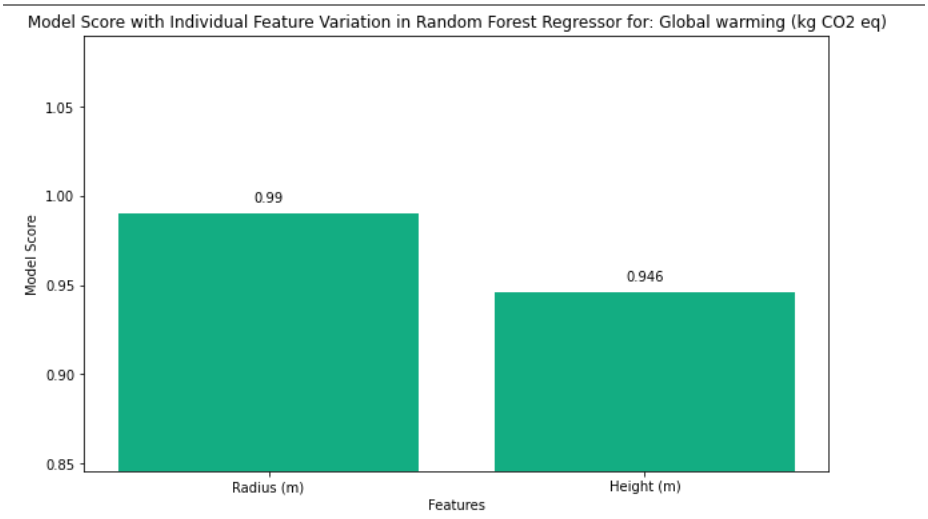
R-squared for Smog (kg O_3 eq): 0.9696

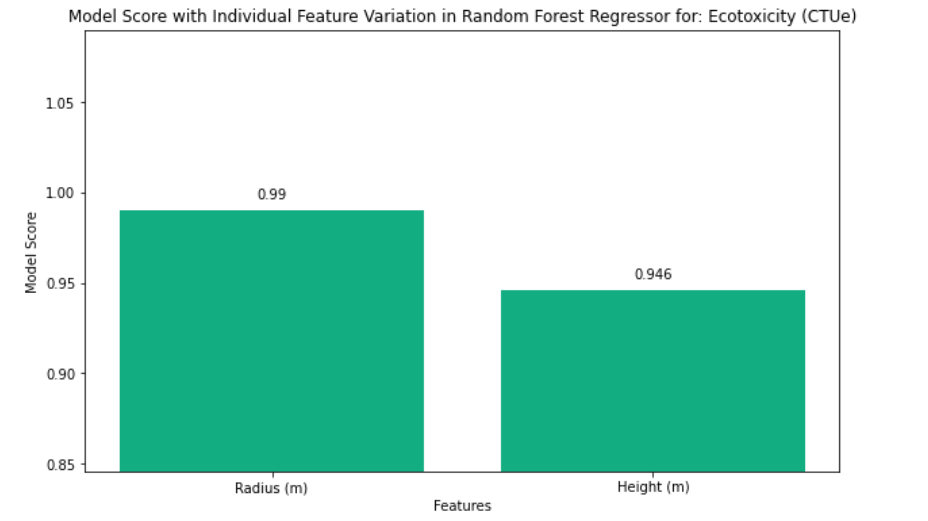
MSE for Smog (kg O_3 eq): 1948.66

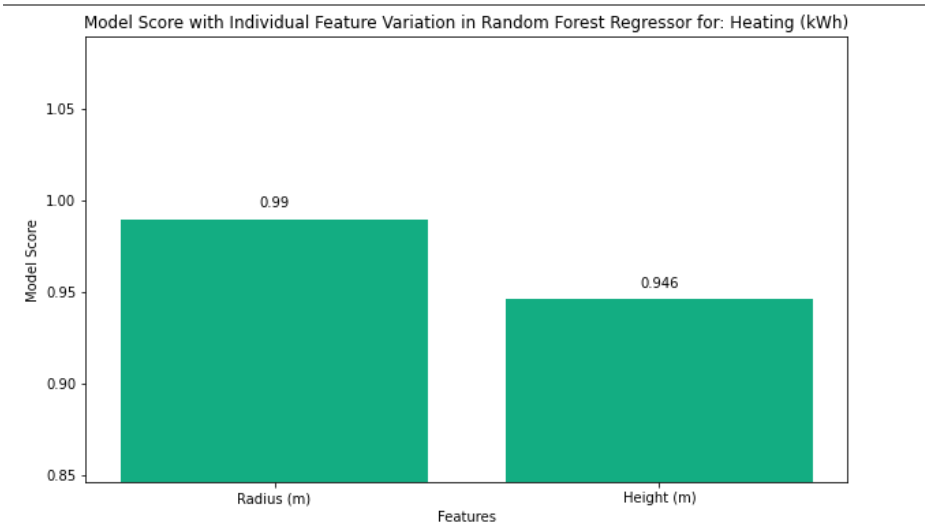
Diagram 4-6: Model Score with individual Features in Random Data (Sphere)

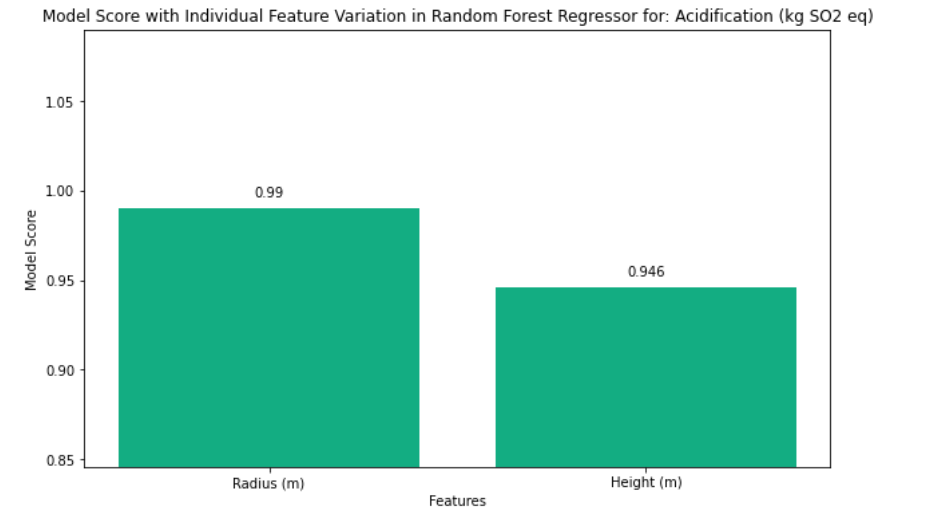


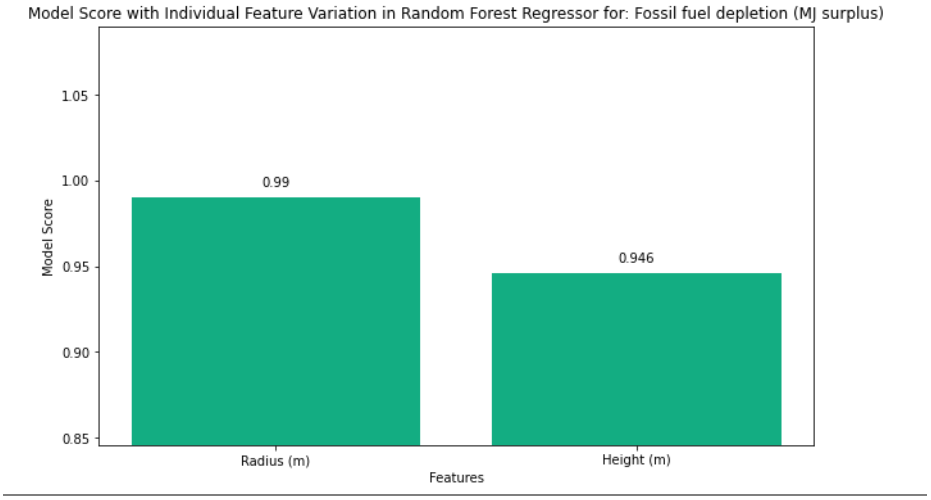

Model Score with Individual Feature Variation in Random Forest Regressor for: Thermal Load (kWh)
Model Score
1.05
1.00
0.95
0.90
0.85
0.99
0.946
Radius (m)
Height (m)
Features


Model Score with Individual Feature Variation in Random Forest Regressor for: Global warming (kg CO2 eq)
Model Score
1.05
1.00
0.95
0.90
0.85
0.99
0.946
Radius (m)
Height (m)
Features


Model Score with Individual Feature Variation in Random Forest Regressor for: Ecotoxicity (CTUe)
Model Score
1.05
1.00
0.95
0.90
0.85
0.99
0.946
Radius (m)
Height (m)
Features


Model Score with Individual Feature Variation in Random Forest Regressor for: Heating (kWh)
Model Score
1.05
1.00
0.95
0.90
0.85
0.99
0.946
Radius (m)
Height (m)
Features


Model Score with Individual Feature Variation in Random Forest Regressor for: Acidification (kg SO2 eq)
Model Score
1.05
1.00
0.95
0.90
0.85
0.99
0.946
Radius (m)
Height (m)
Features


Model Score with Individual Feature Variation in Random Forest Regressor for: Fossil fuel depletion (MJ surplus)
Model Score
1.05
1.00
0.95
0.90
0.85
0.99
0.946
Radius (m)
Height (m)
Features

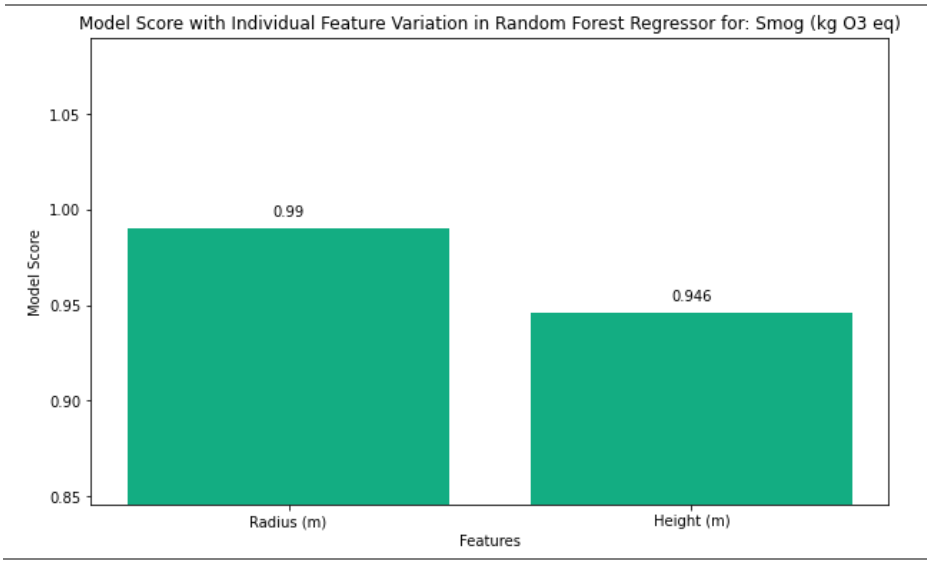


Diagram 4-7 :FRF & XGBoost (Sphere)

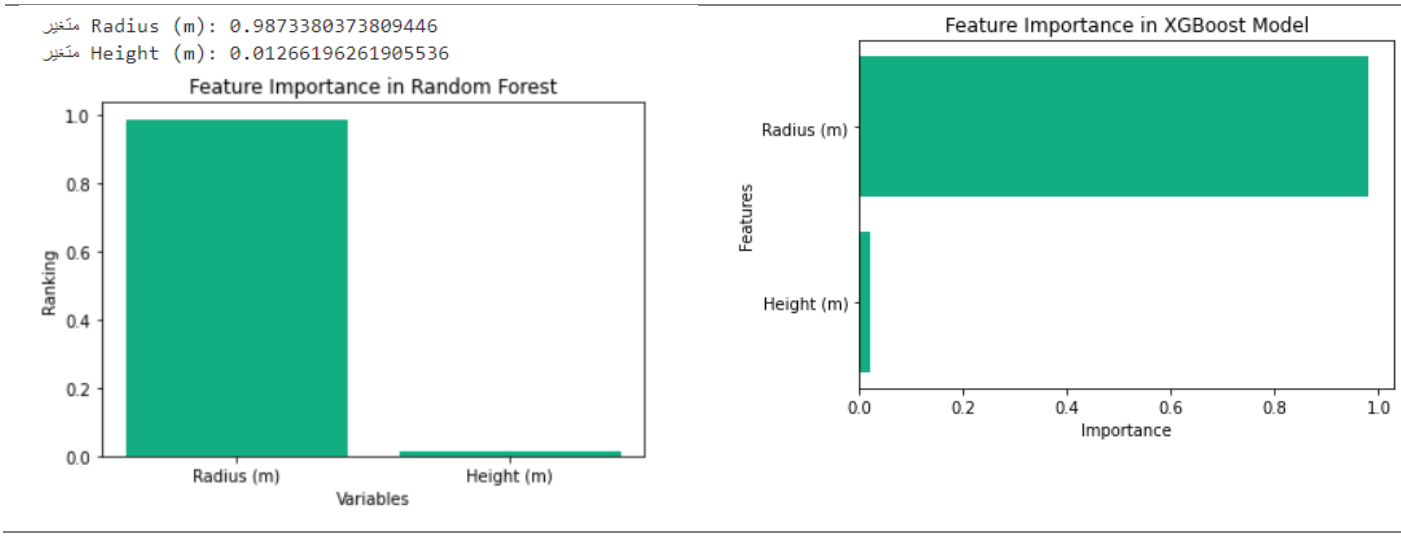
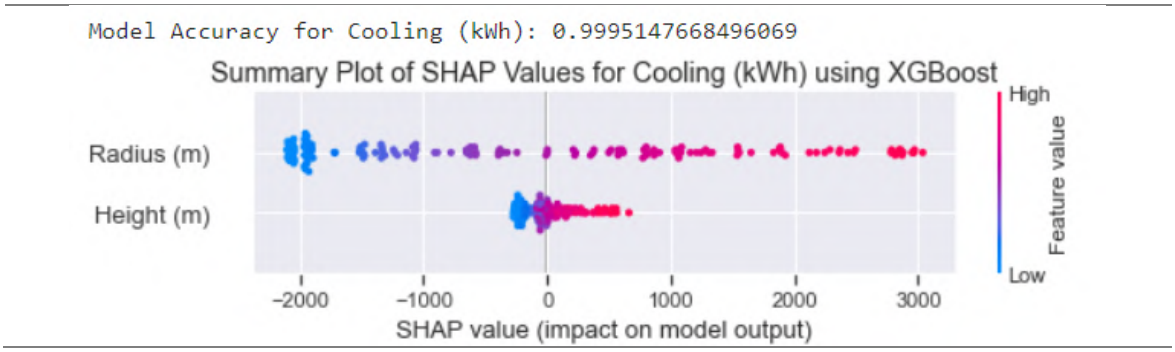
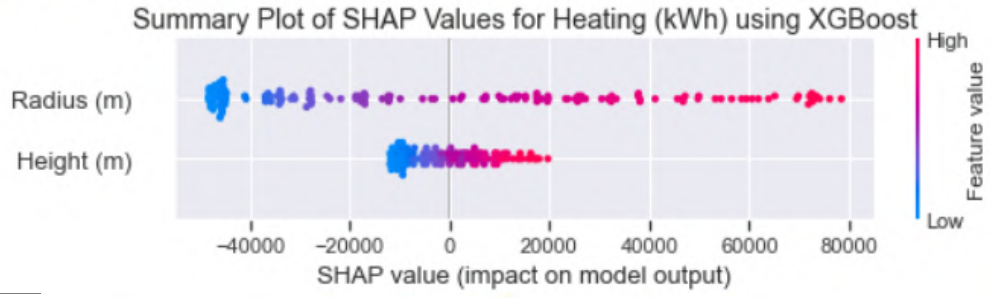


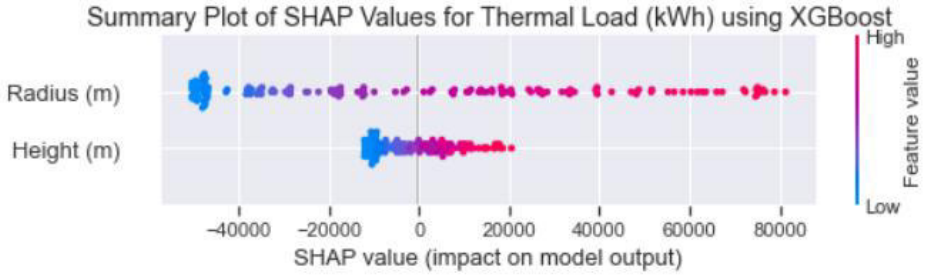
Diagram 4-8: SHAP diagram (Sphere)



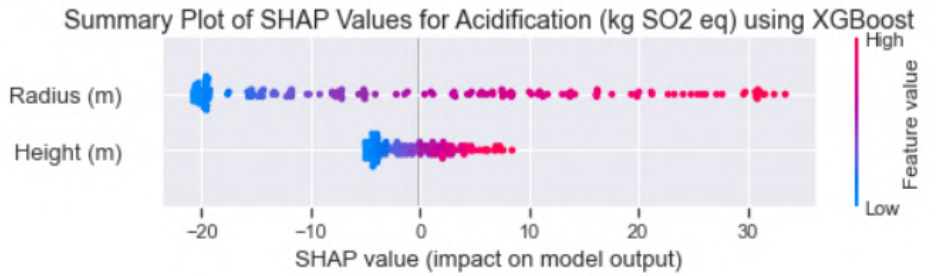
```
Model Accuracy for Heating (kWh): 0.9996672255478527
```



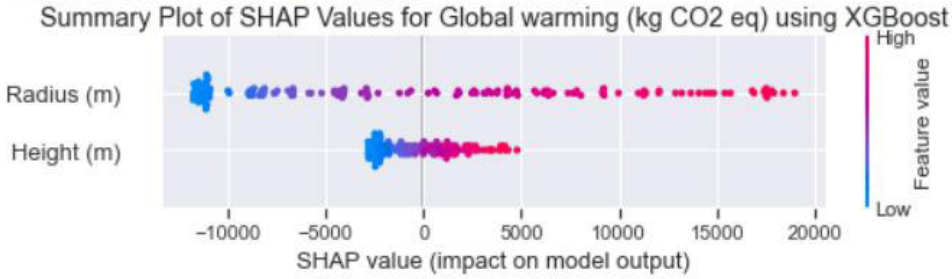

```
Model Accuracy for Thermal Load (kWh): 0.9996453707370532
```



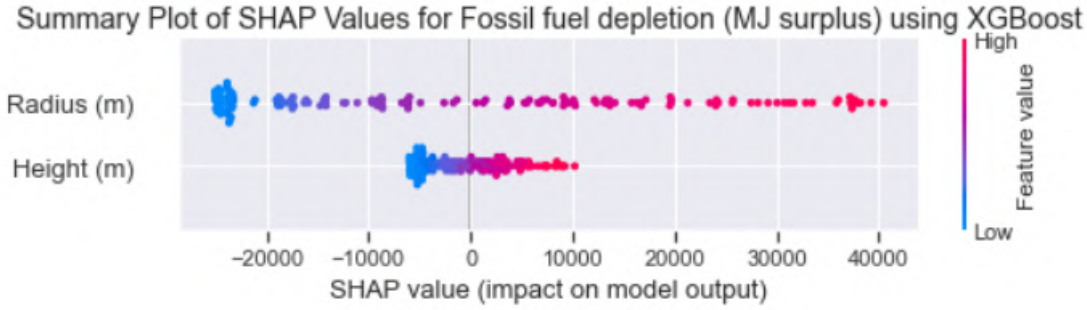

```
Model Accuracy for Acidification (kg SO2 eq): 0.9996453768156586
```




```
Model Accuracy for Global warming (kg CO2 eq): 0.99964537151676
```




```
Model Accuracy for Fossil fuel depletion (MJ surplus): 0.9996455315301208
```



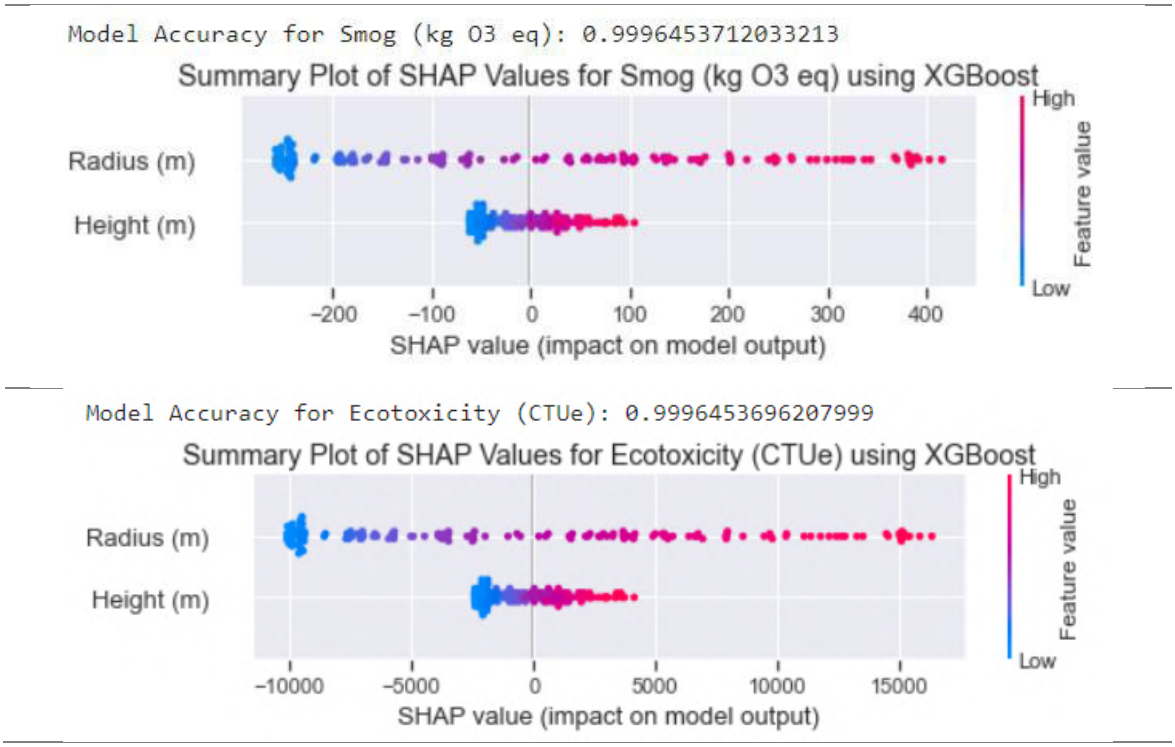


Diagram 4-9: Heatmap- Pearson Correlation

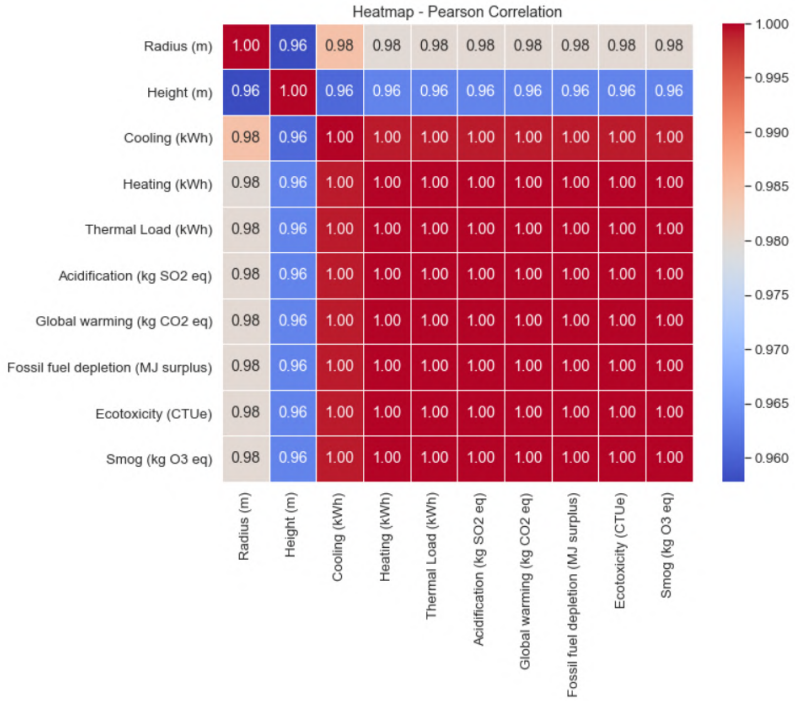


Diagram 4-10: Spearman Correlation (Sphere)

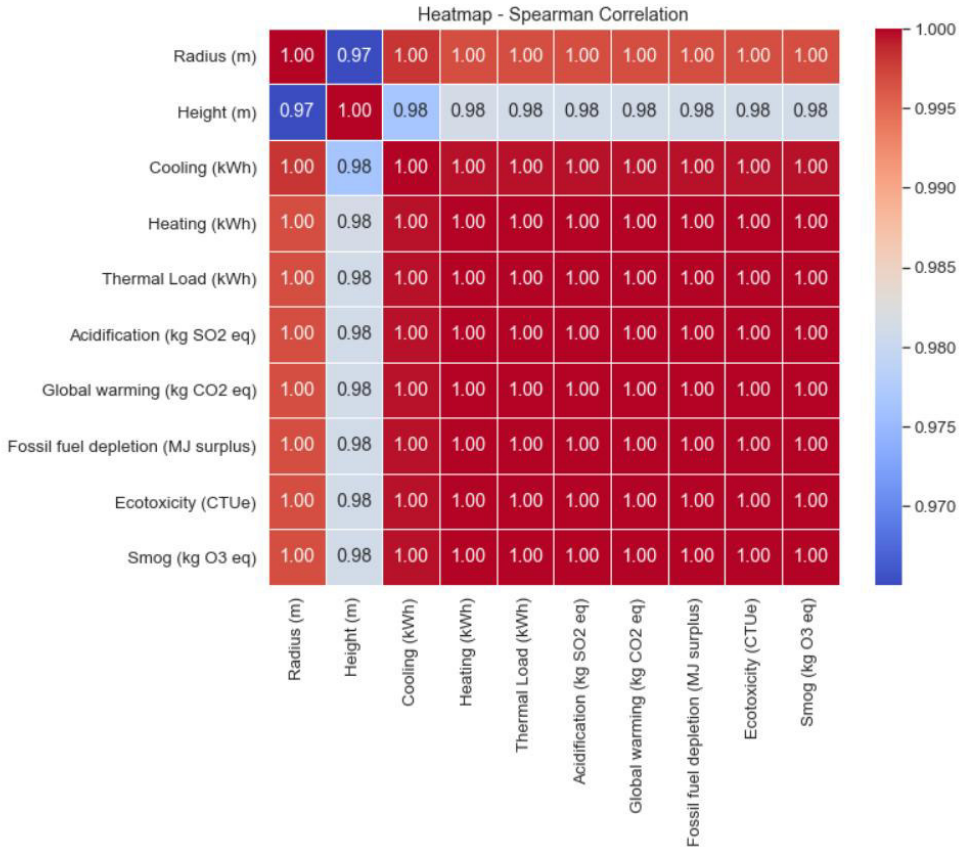


Diagram 4-11: Relative Importance of features for each goal (Sphere)

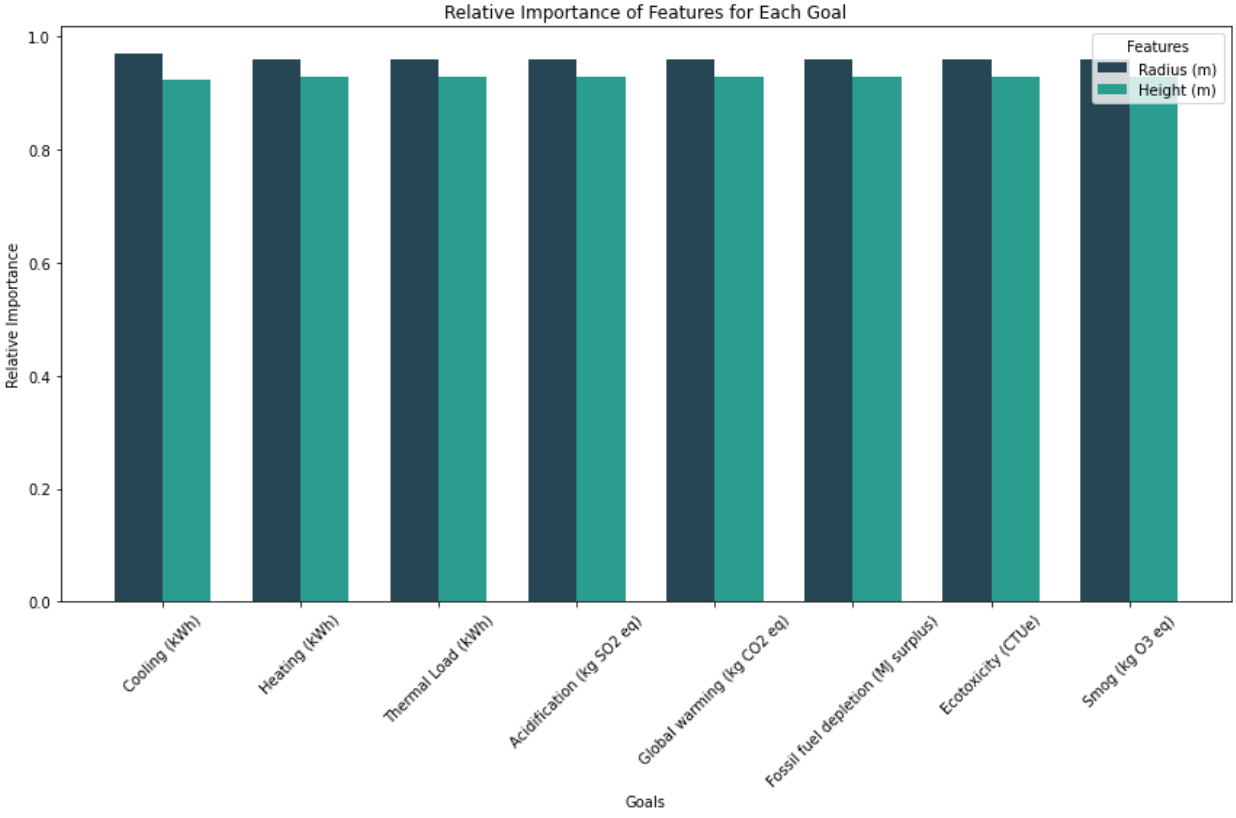


Diagram 4-12: Scatter plots (Cask)

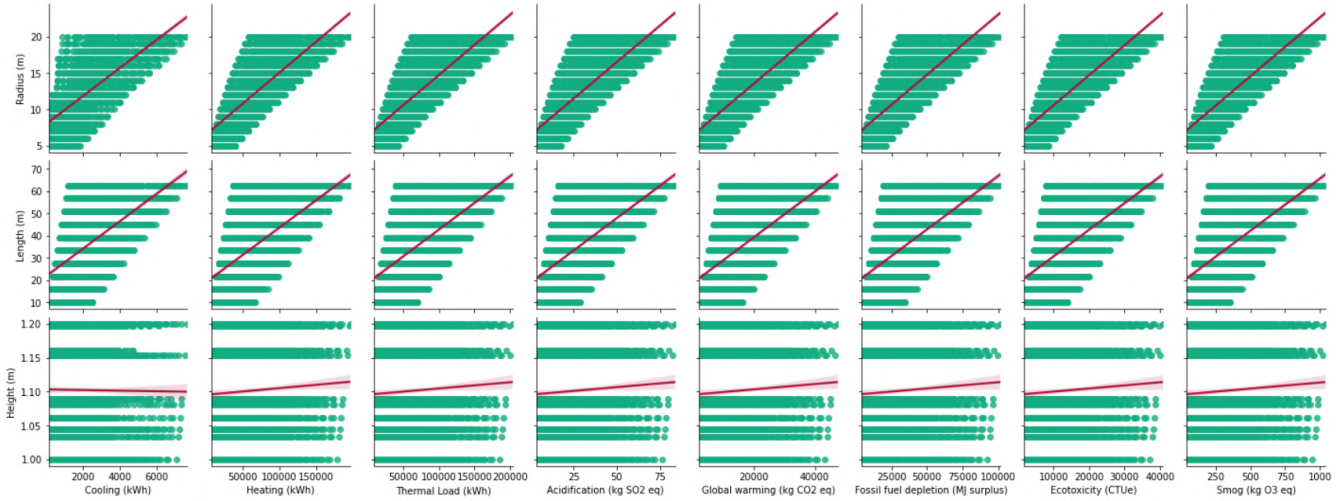
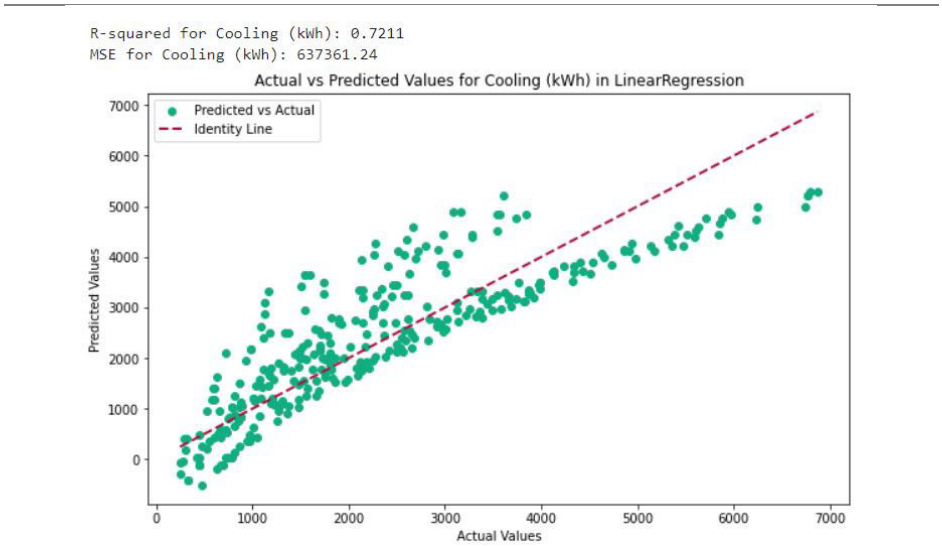
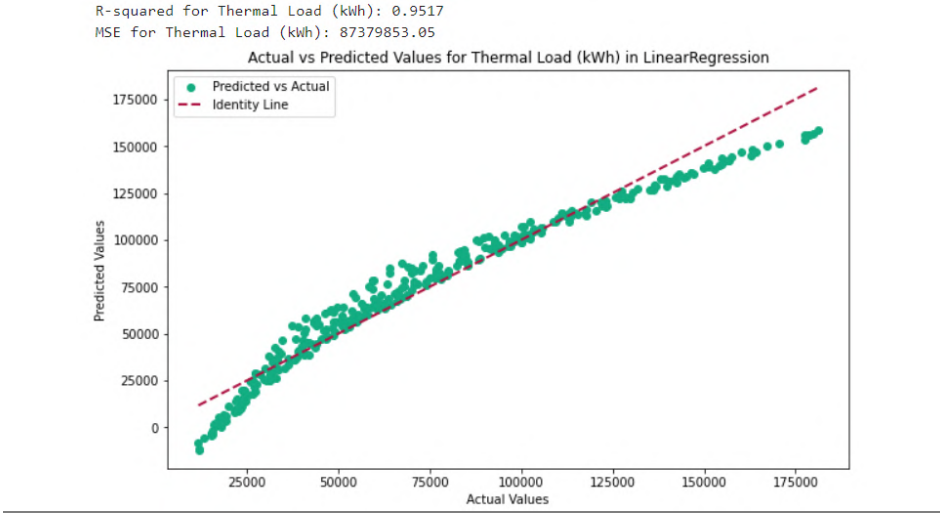
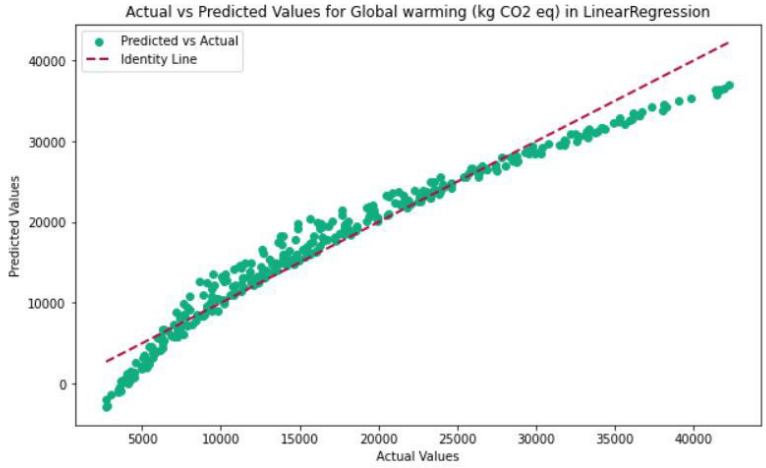


Diagram 4-13: Actual values vs predicted values (Cask)

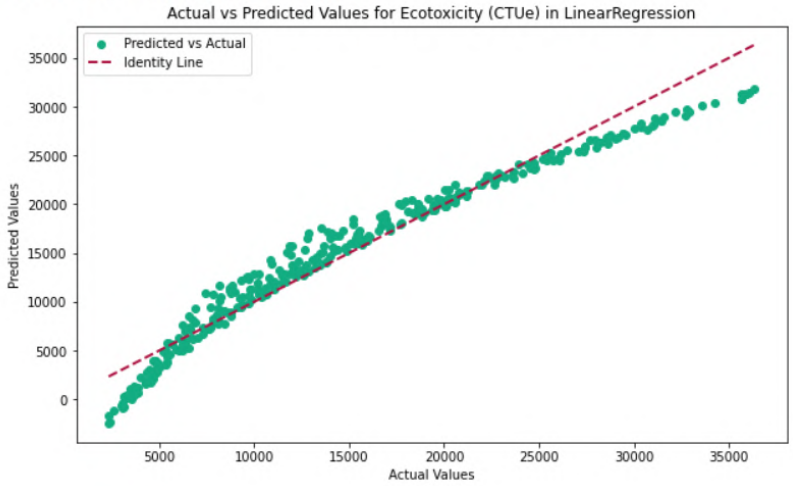




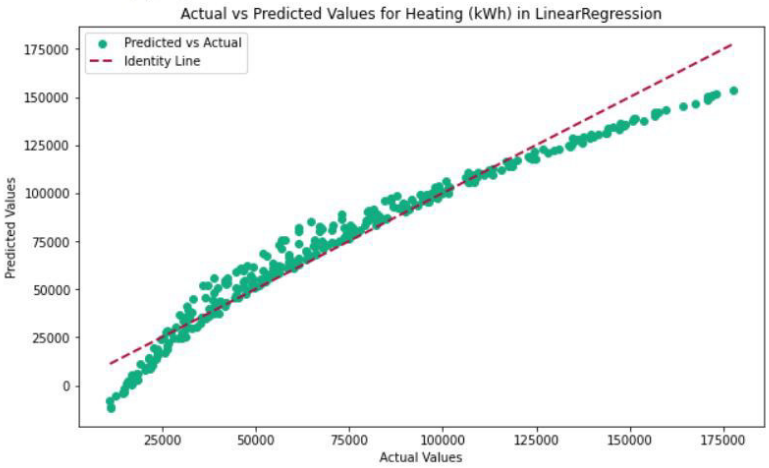
```
R-squared for Global warming (kg CO2 eq): 0.9517
MSE for Global warming (kg CO2 eq): 4753562.63
```



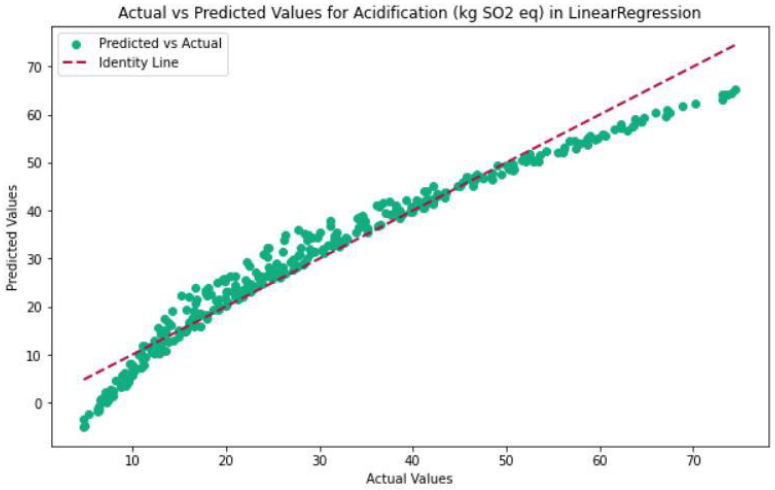

```
R-squared for Ecotoxicity (CTUe): 0.9517
MSE for Ecotoxicity (CTUe): 3518900.28
```



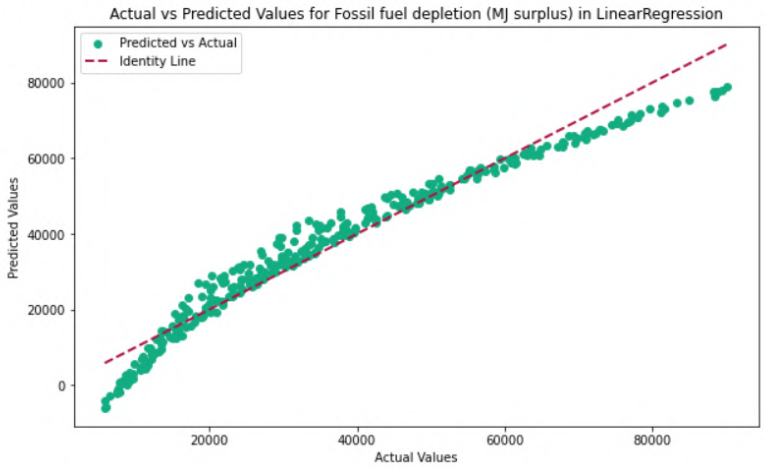

```
R-squared for Heating (kWh): 0.9514
MSE for Heating (kWh): 82616073.36
```



```
R-squared for Acidification (kg SO2 eq): 0.9517
MSE for Acidification (kg SO2 eq): 14.80
```




```
R-squared for Fossil fuel depletion (MJ surplus): 0.9517
MSE for Fossil fuel depletion (MJ surplus): 21638837.54
```




```
R-squared for Smog (kg O3 eq): 0.9517
MSE for Smog (kg O3 eq): 2285.49
```

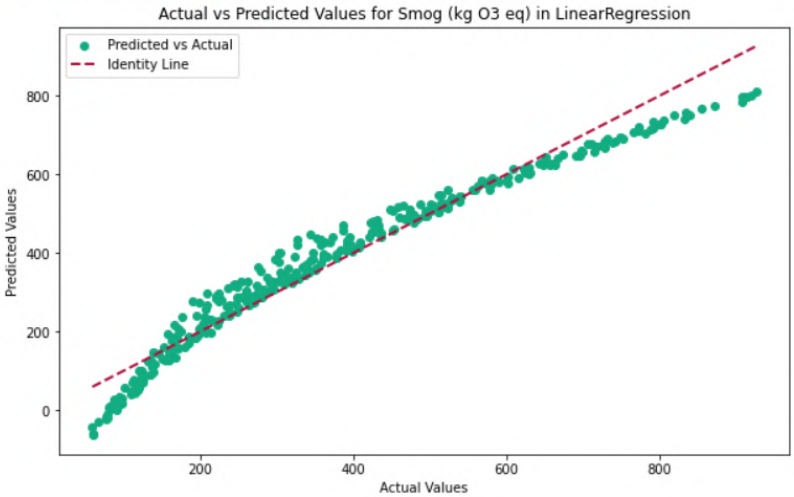
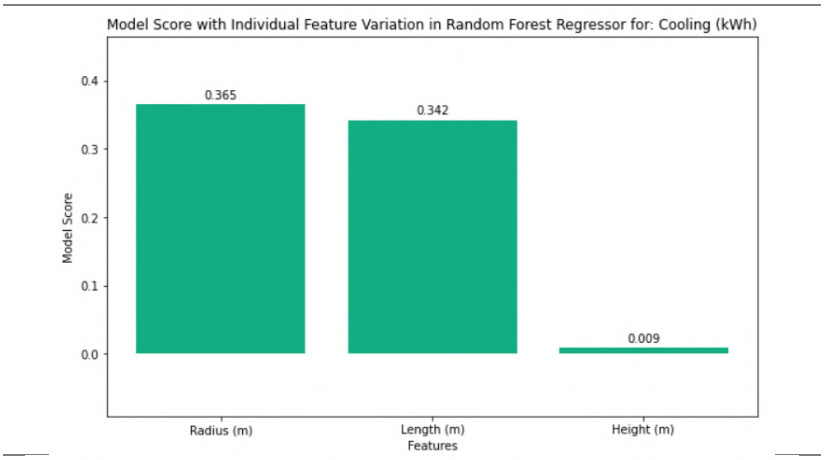
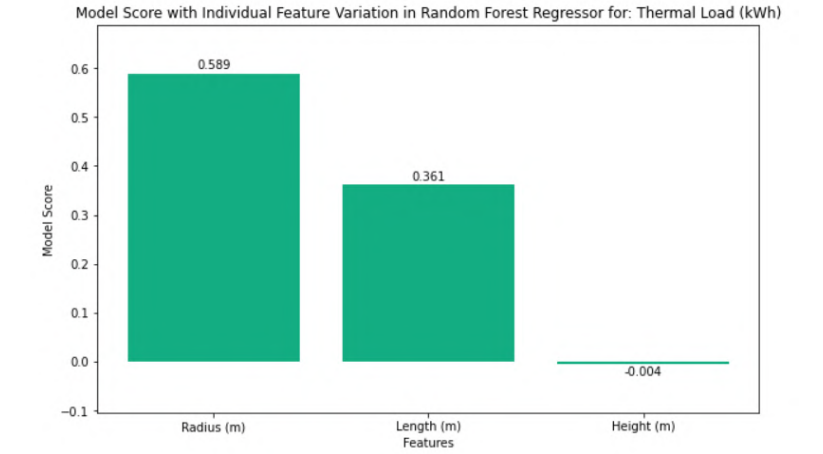
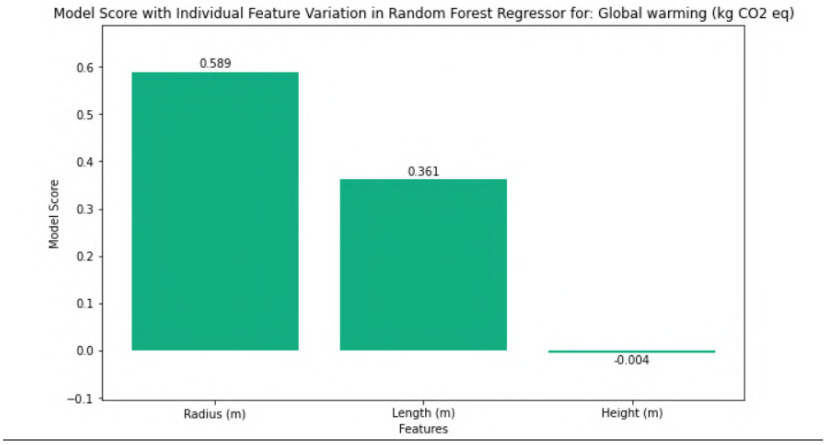
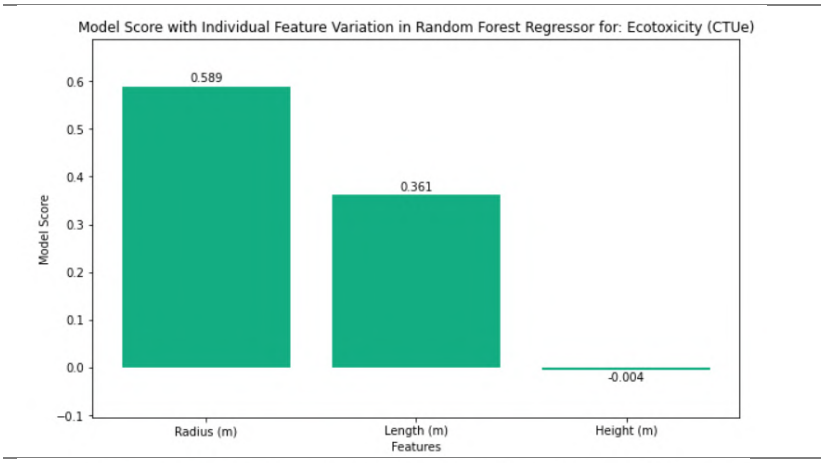


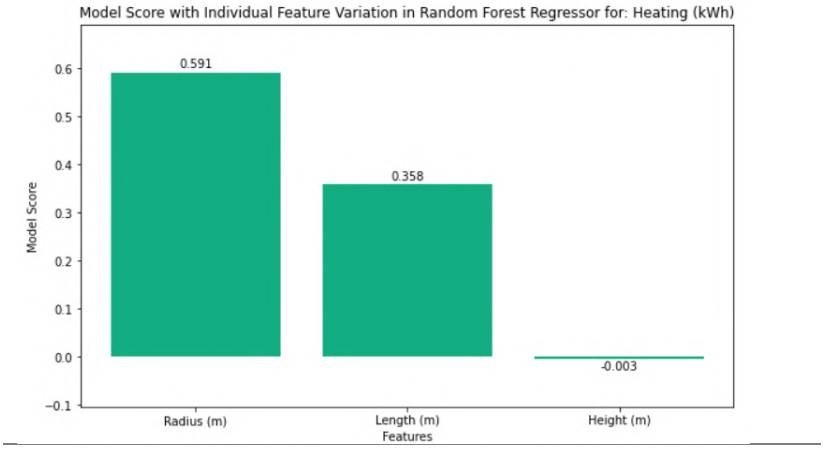
Diagram 4-14: Model Score with individual Features in Random Data (Cask)

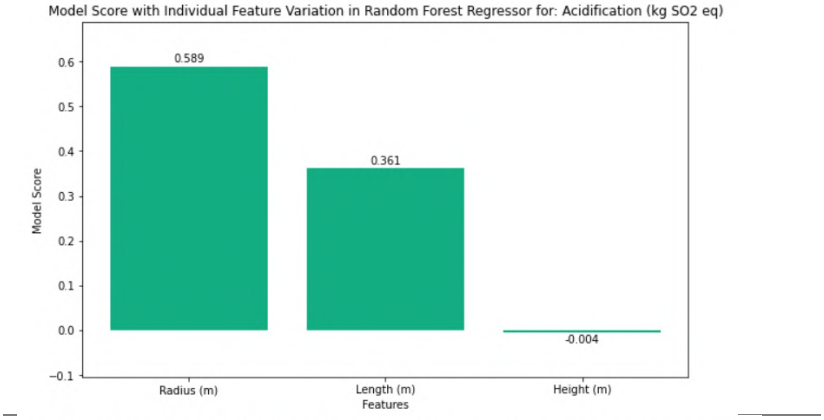


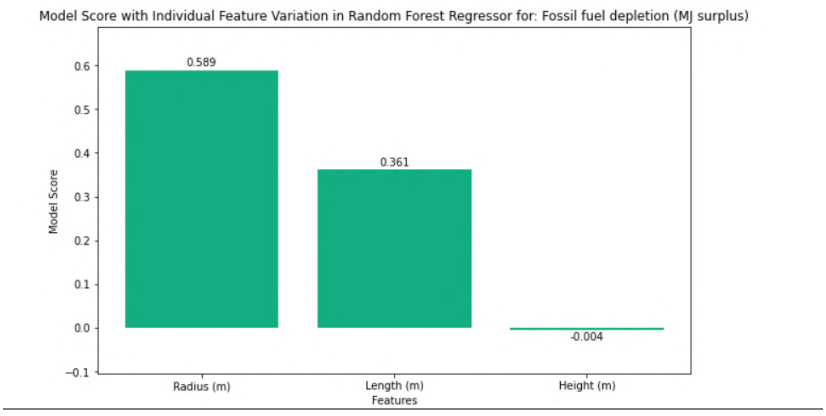





Model Score with Individual Feature Variation in Random Forest Regressor for: Ecotoxicity (CTUe)
Model Score
0.589
0.361
-0.004
Radius (m)
Length (m)
Height (m)
Features


Model Score with Individual Feature Variation in Random Forest Regressor for: Heating (kWh)
Model Score
0.591
0.358
-0.003
Radius (m)
Length (m)
Height (m)
Features


Model Score with Individual Feature Variation in Random Forest Regressor for: Acidification (kg SO2 eq)
Model Score
0.589
0.361
-0.004
Radius (m)
Length (m)
Height (m)
Features


Model Score with Individual Feature Variation in Random Forest Regressor for: Fossil fuel depletion (MJ surplus)
Model Score
0.589
0.361
-0.004
Radius (m)
Length (m)
Height (m)
Features

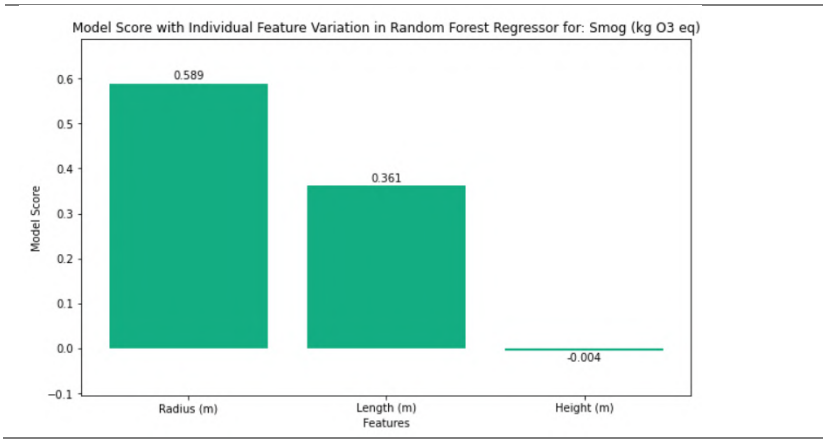


Diagram 4-15: FRF & XGBoost (Cask)

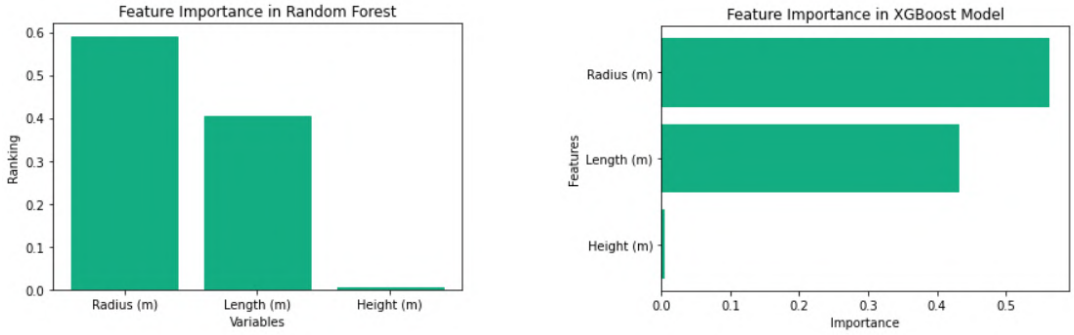
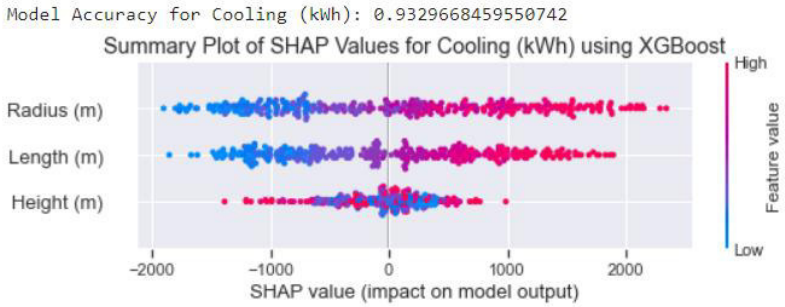
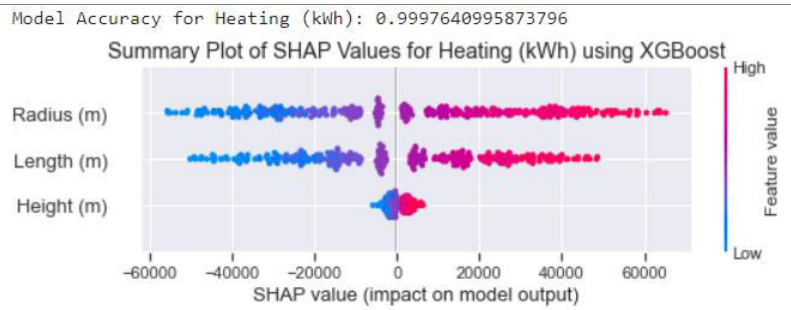
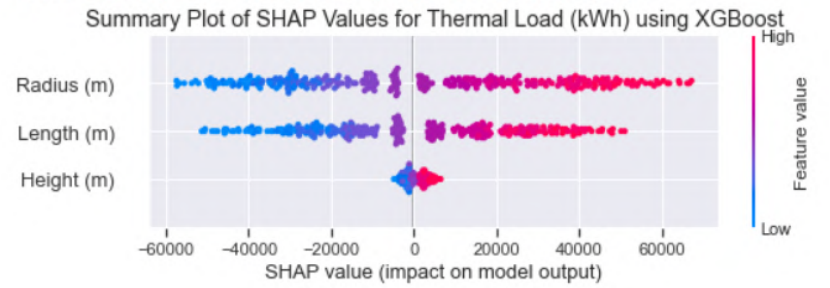


Diagram 4-16: SHAP Diagram (Cask)

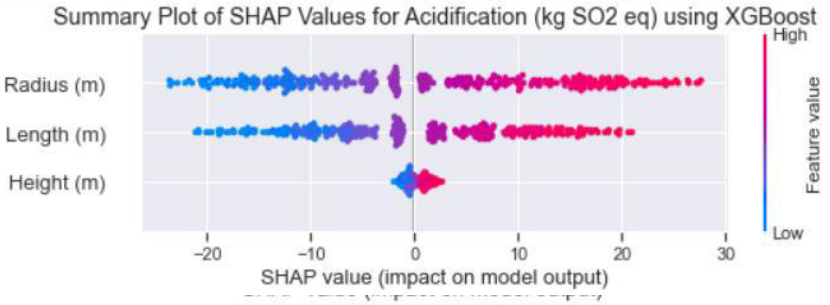




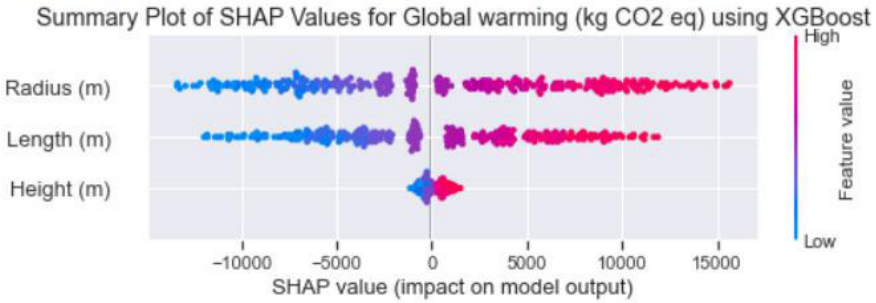
```
Model Accuracy for Thermal Load (kWh): 0.9996810992304704
```




```
Model Accuracy for Acidification (kg SO2 eq): 0.9996809927804509
```




```
Model Accuracy for Global warming (kg CO2 eq): 0.9996809897854073
```




```
Model Accuracy for Fossil fuel depletion (MJ surplus): 0.9996811008333885
```

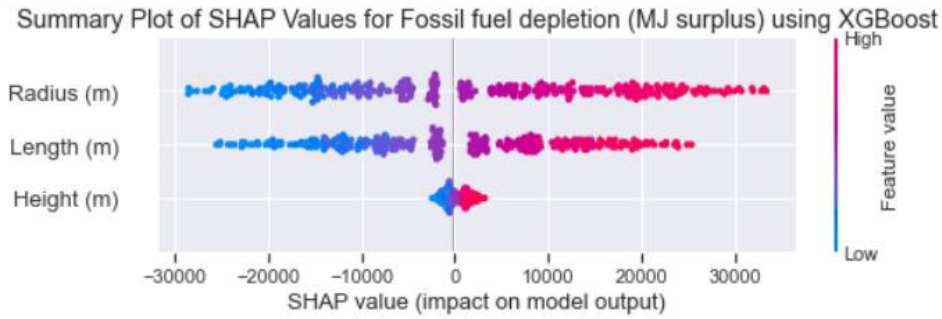


Diagram 4-17 : Heatmap- Pearson Correlation (Cask)

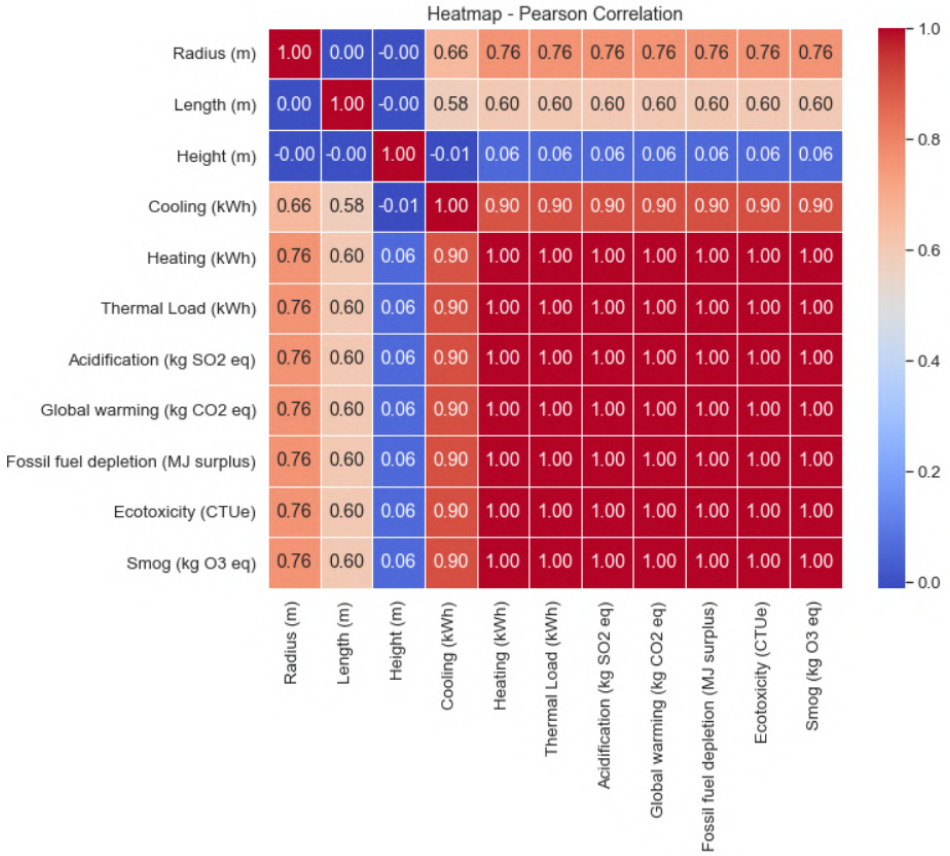


Diagram 4-18: Heatmap-spearman Correlation (Cask)

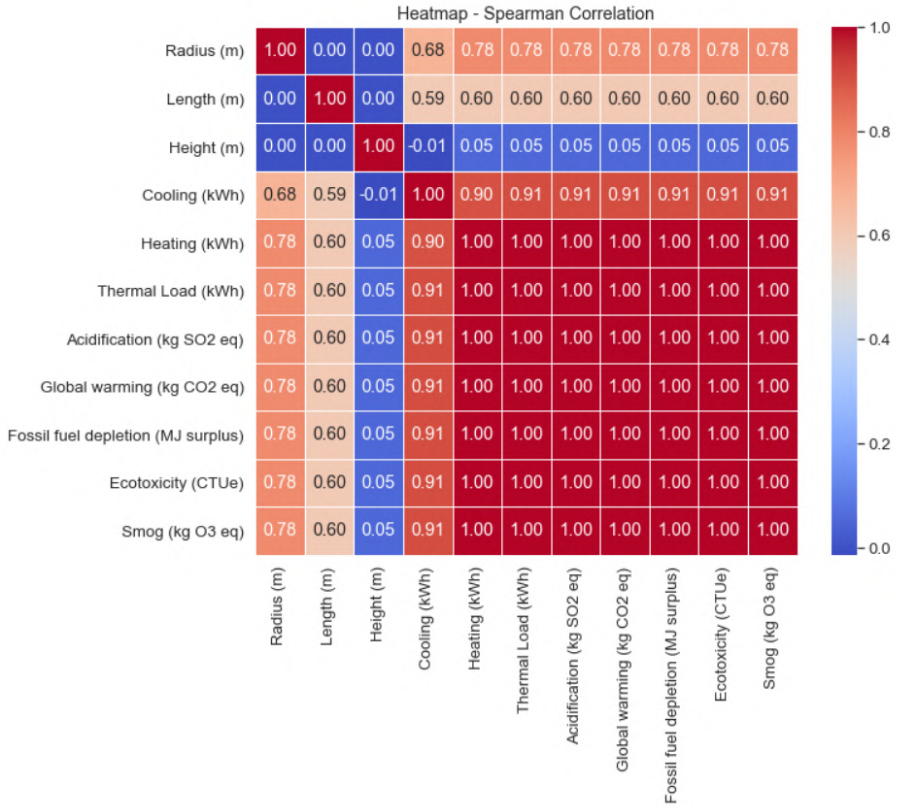


Diagram 4-19: Relative Importance of features for each goal (Cask)

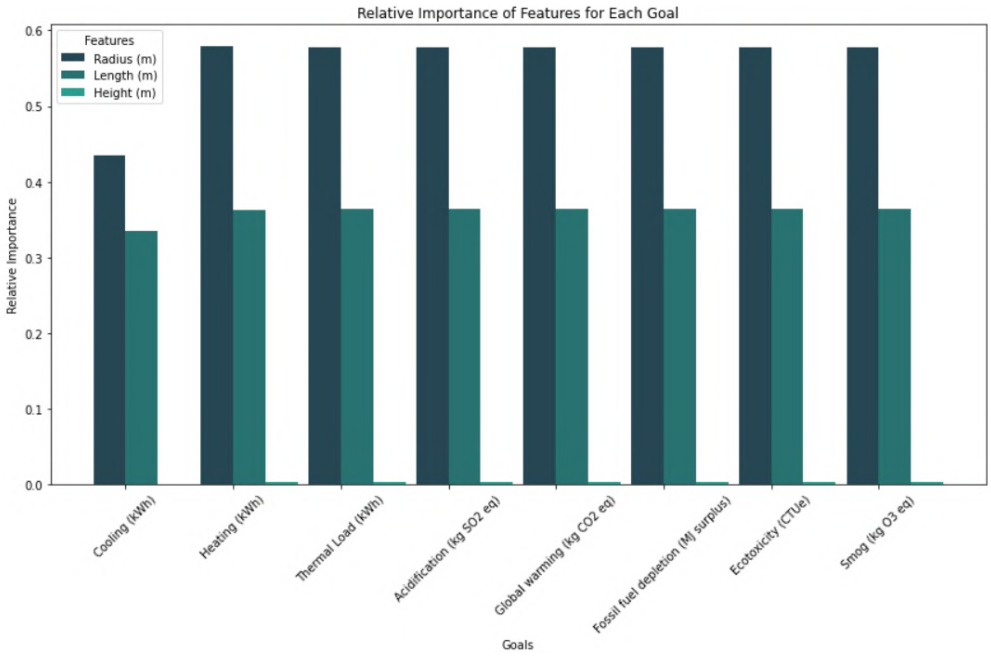


Diagram 4-20: scatter plots (Cube)

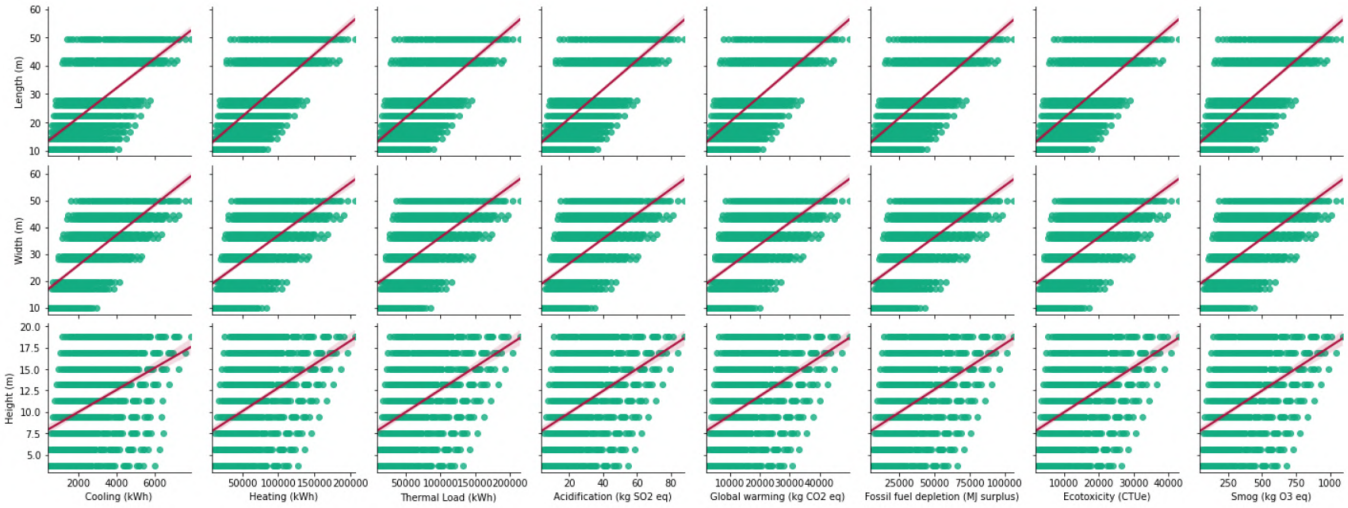
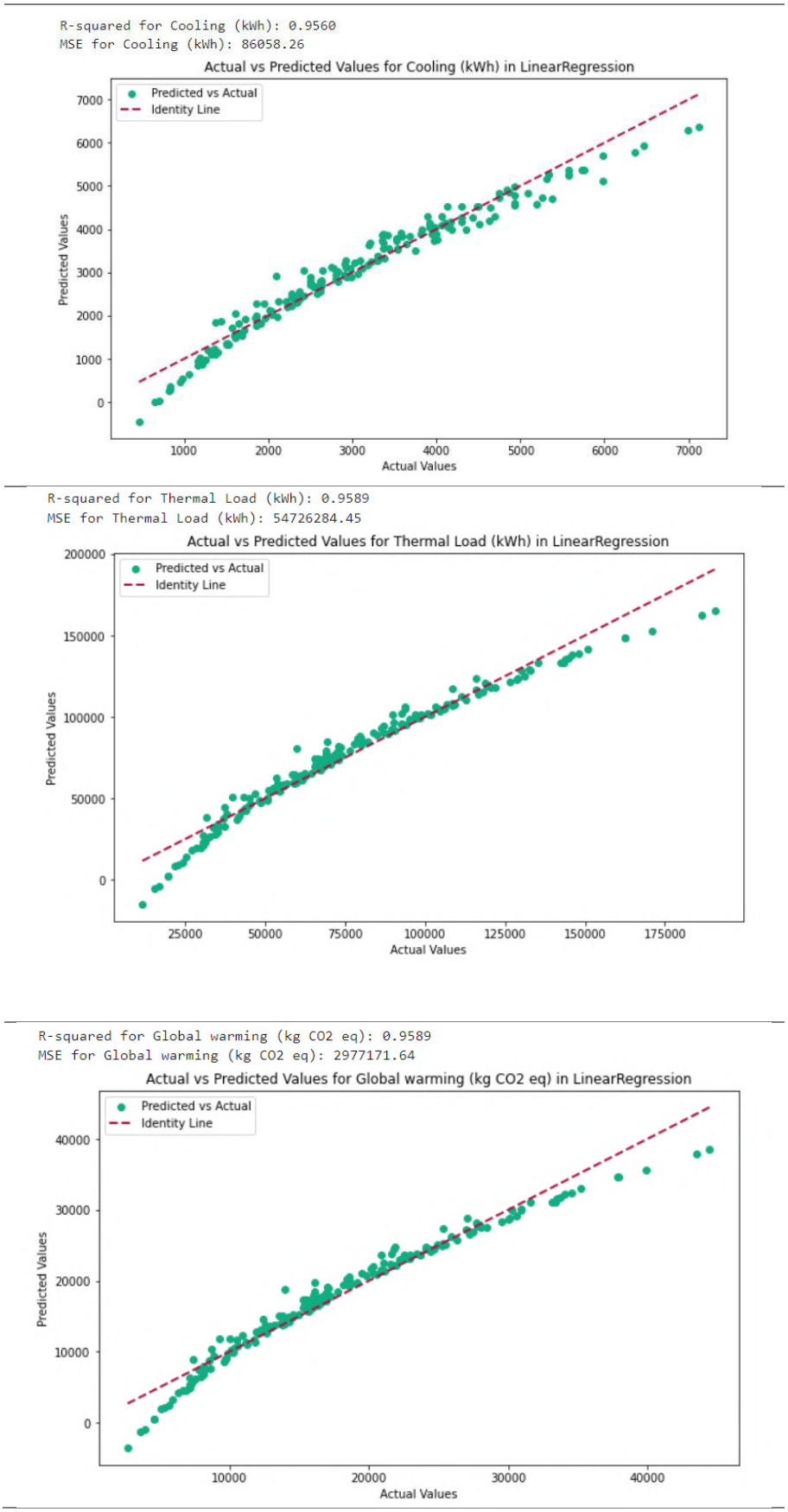
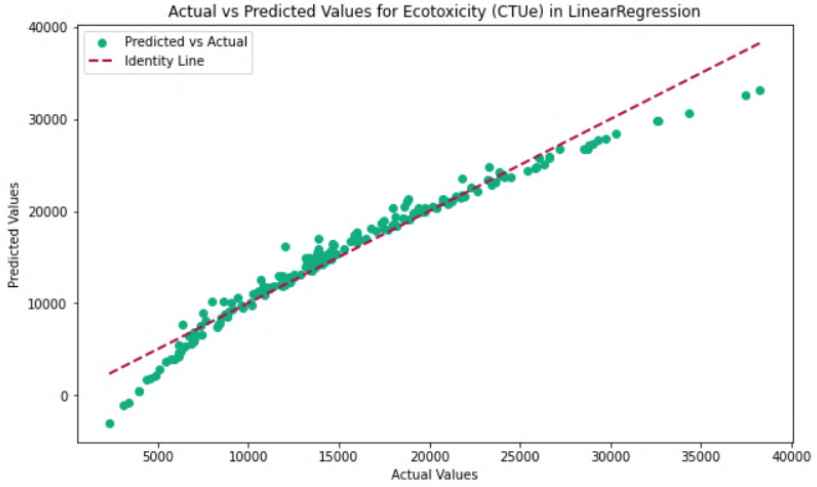


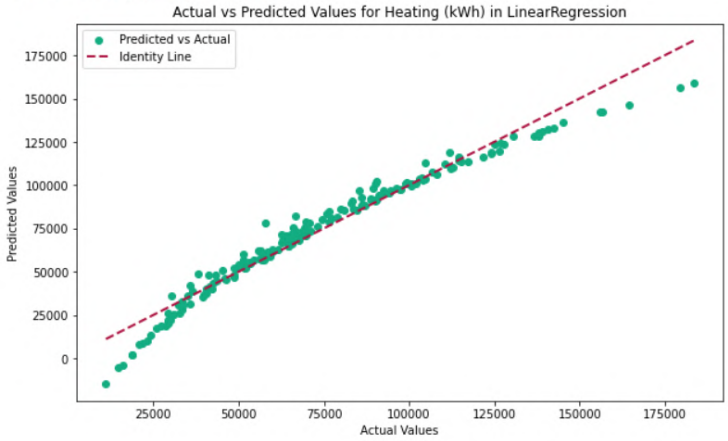
Diagram 4-21: Actual values vs predicted values (Cube)



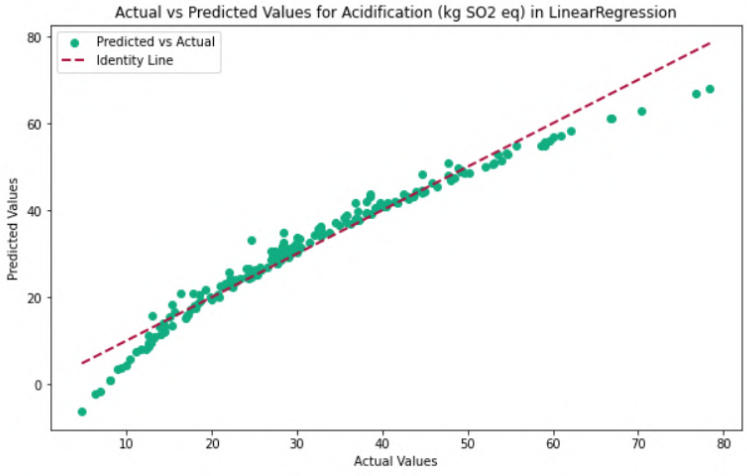
```
R-squared for Ecotoxicity (CTUe): 0.9589
MSE for Ecotoxicity (CTUe): 2203898.62
```




```
R-squared for Heating (kWh): 0.9583
MSE for Heating (kWh): 51304128.78
```




```
R-squared for Acidification (kg SO2 eq): 0.9589
MSE for Acidification (kg SO2 eq): 9.27
```



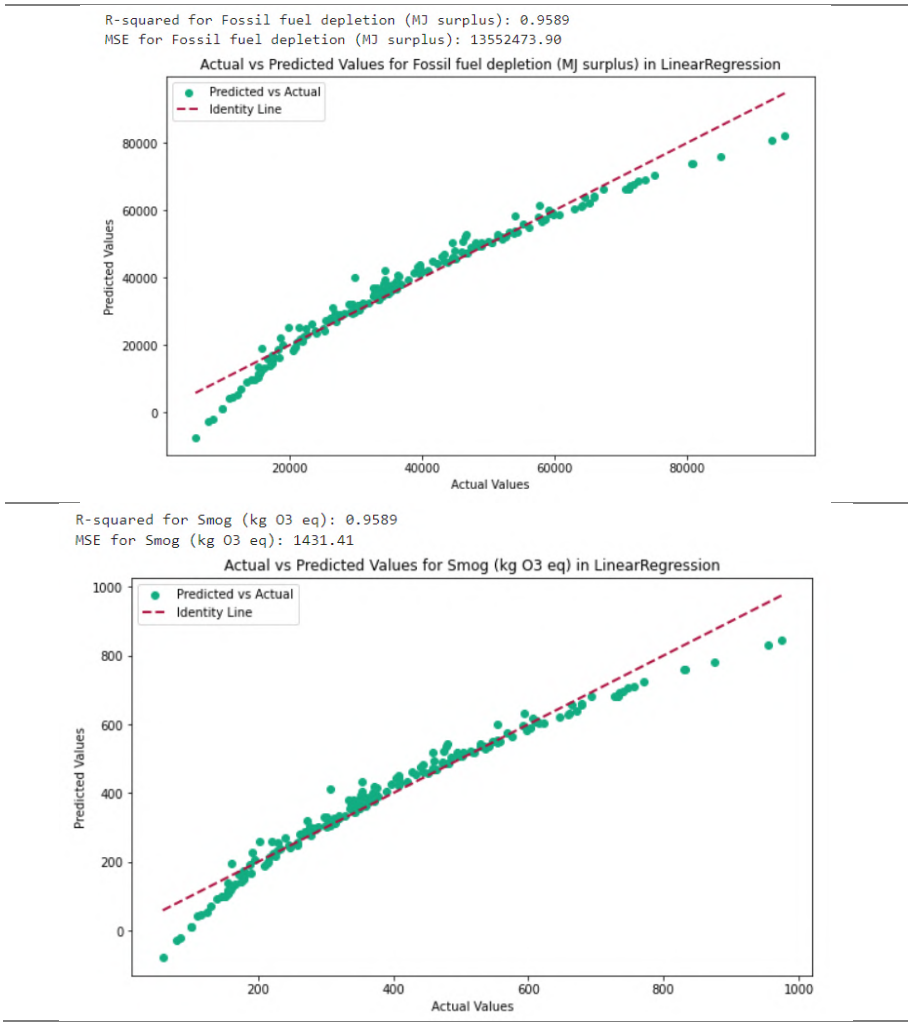
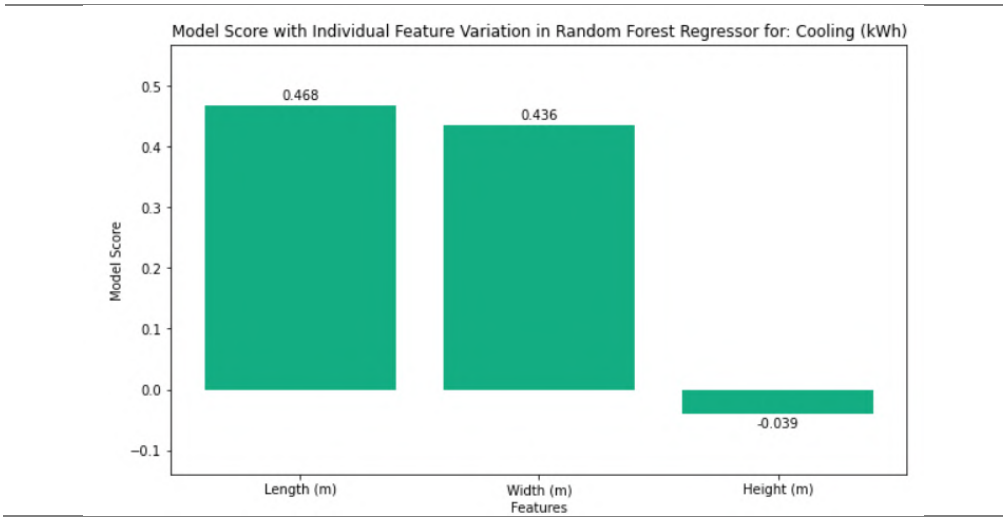
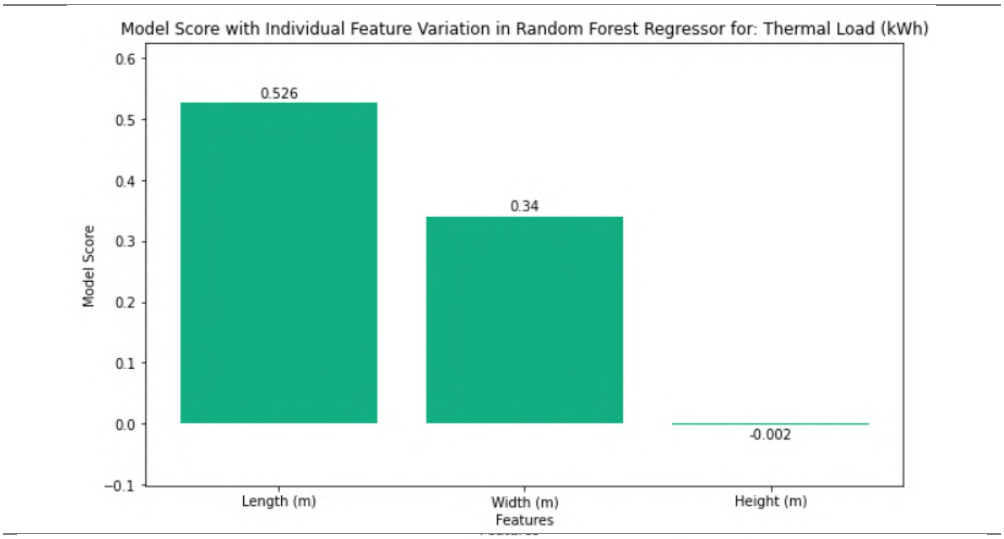
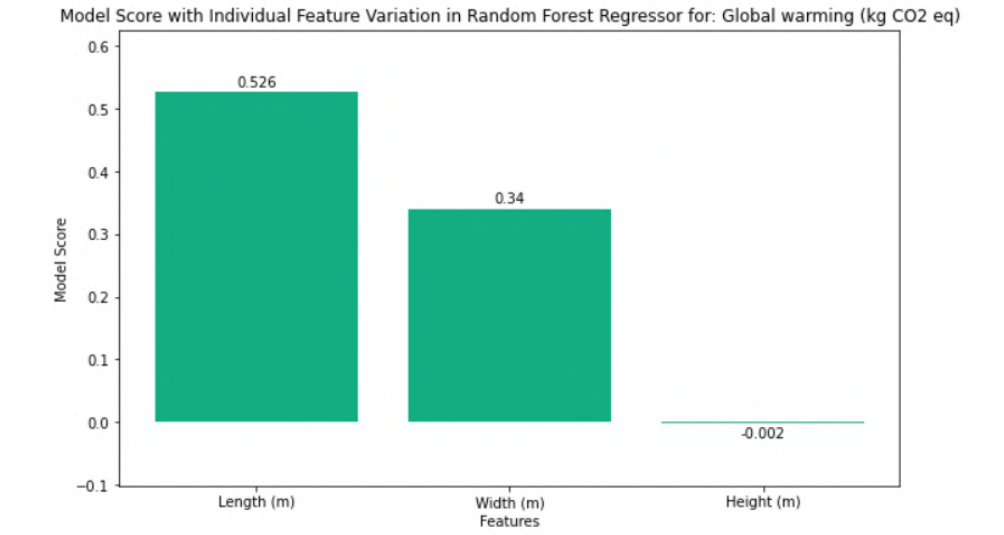
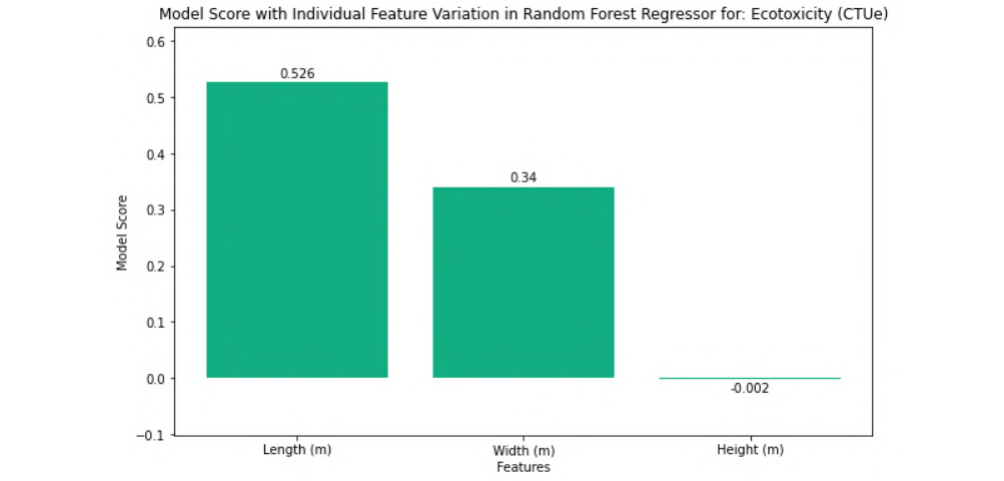


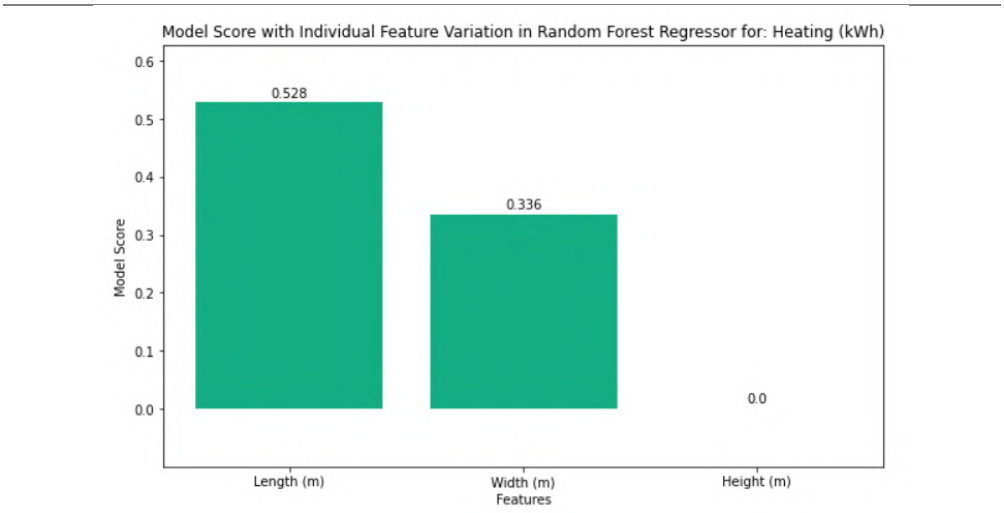
Diagram 4-22: Model Score with individual Features in Random Data (Cube)

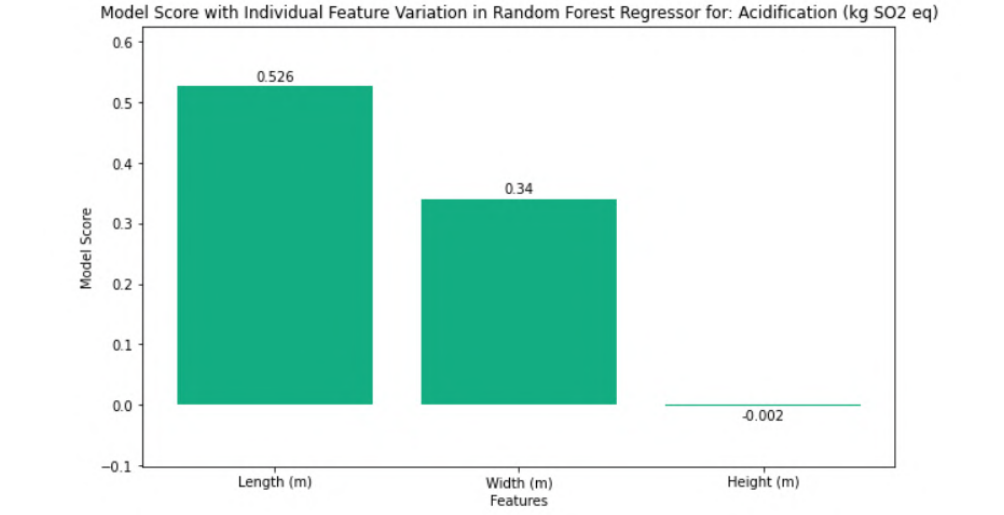


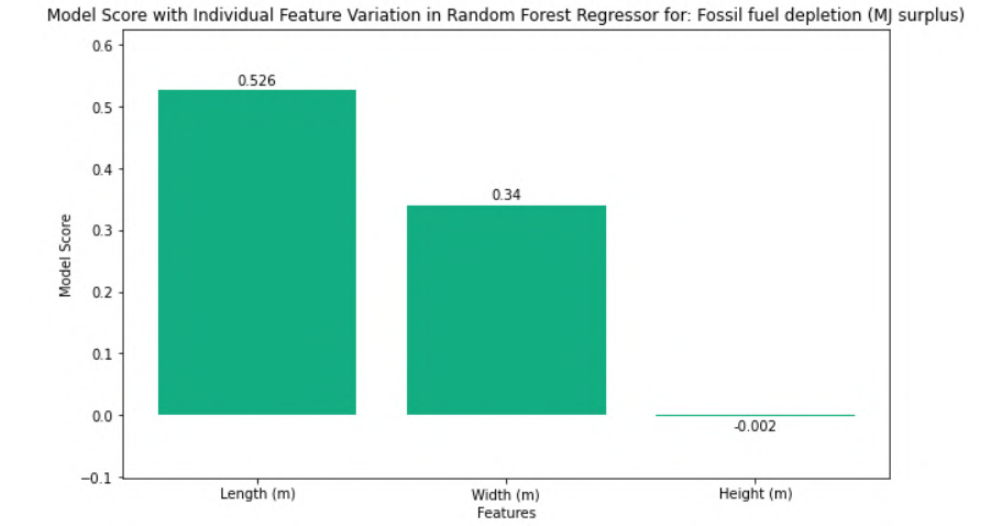

Model Score with Individual Feature Variation in Random Forest Regressor for: Thermal Load (kWh)
Model Score
0.6
0.5
0.4
0.3
0.2
0.1
0.0
−0.1
0.526
0.34
-0.002
Length (m)
Width (m)
Height (m)
Features


Model Score with Individual Feature Variation in Random Forest Regressor for: Global warming (kg CO2 eq)
Model Score
0.6
0.5
0.4
0.3
0.2
0.1
0.0
−0.1
0.526
0.34
-0.002
Length (m)
Width (m)
Height (m)
Features


Model Score with Individual Feature Variation in Random Forest Regressor for: Ecotoxicity (CTUe)
Model Score
0.6
0.5
0.4
0.3
0.2
0.1
0.0
−0.1
0.526
0.34
-0.002
Length (m)
Width (m)
Height (m)
Features


Model Score with Individual Feature Variation in Random Forest Regressor for: Heating (kWh)
Model Score
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.528
0.336
0.0
Length (m)
Width (m)
Height (m)
Features


Model Score with Individual Feature Variation in Random Forest Regressor for: Acidification (kg SO2 eq)
Model Score
0.6
0.5
0.4
0.3
0.2
0.1
0.0
−0.1
0.526
0.34
-0.002
Length (m)
Width (m)
Height (m)
Features


Model Score with Individual Feature Variation in Random Forest Regressor for: Fossil fuel depletion (MJ surplus)
Model Score
0.6
0.5
0.4
0.3
0.2
0.1
0.0
−0.1
0.526
0.34
-0.002
Length (m)
Width (m)
Height (m)
Features

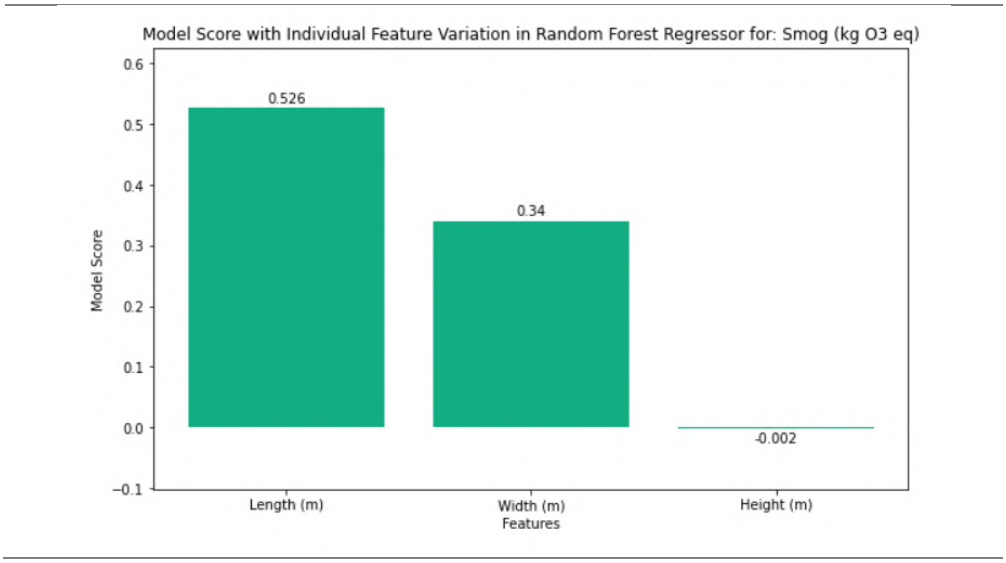


Diagram 4-23: FRE & XGBoost &RF (Cube)

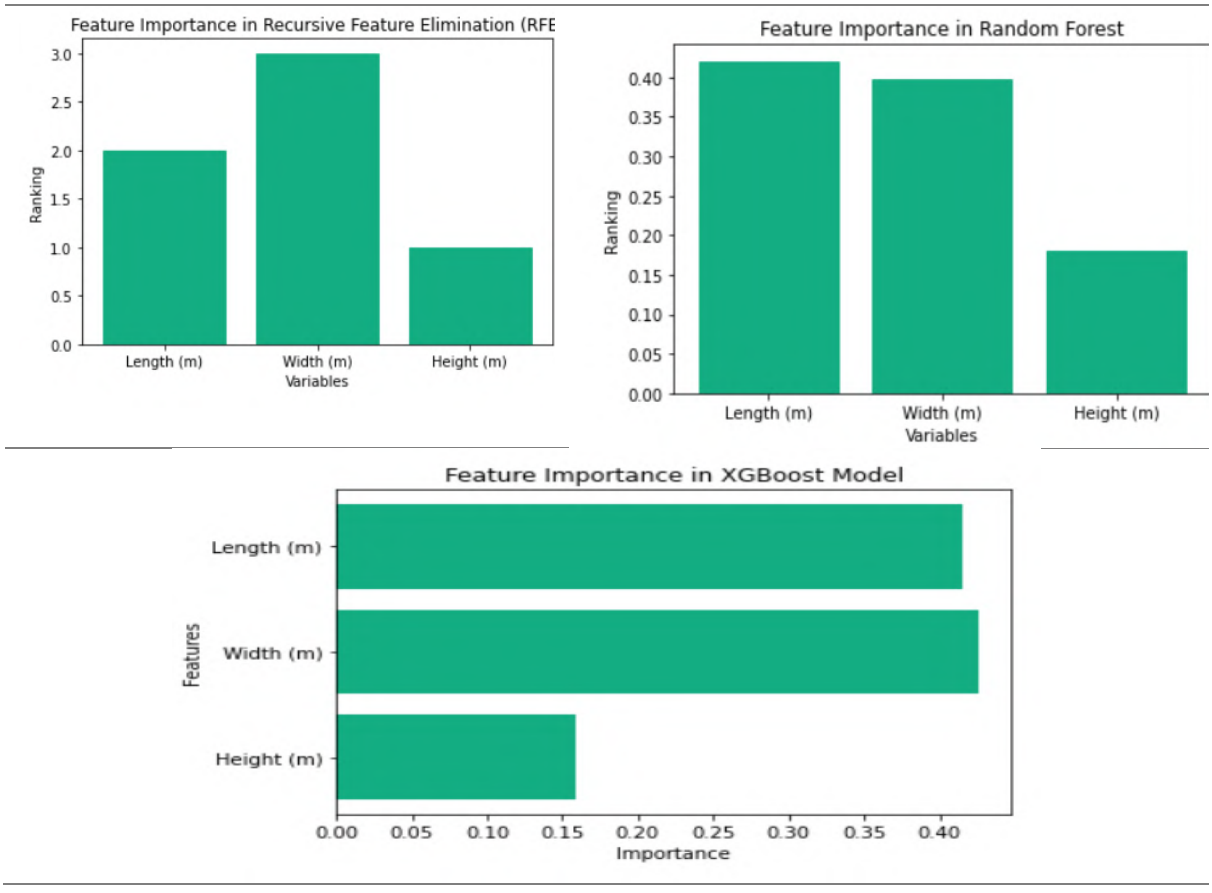
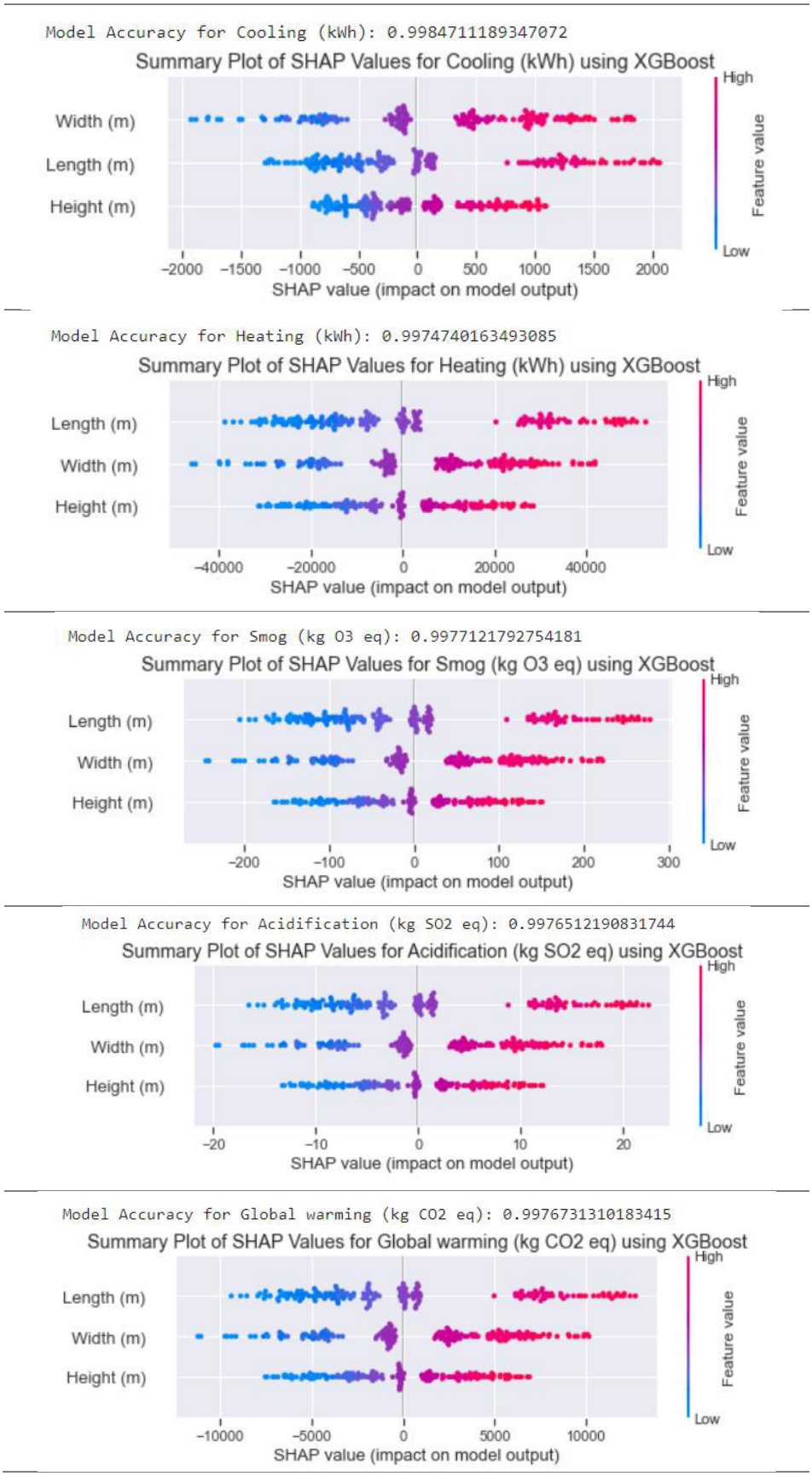
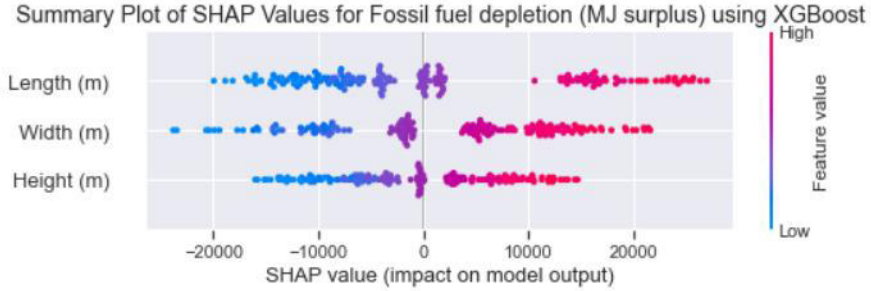


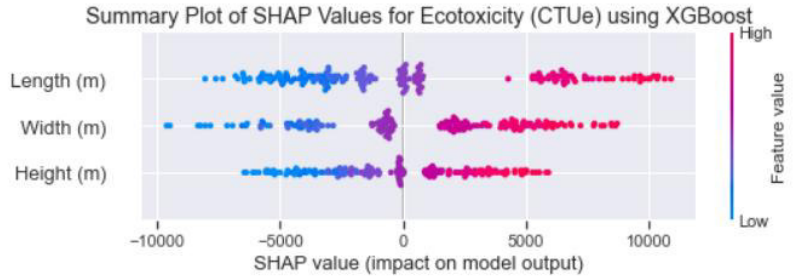
Diagram 4-24: SHAP diagram (Cube)



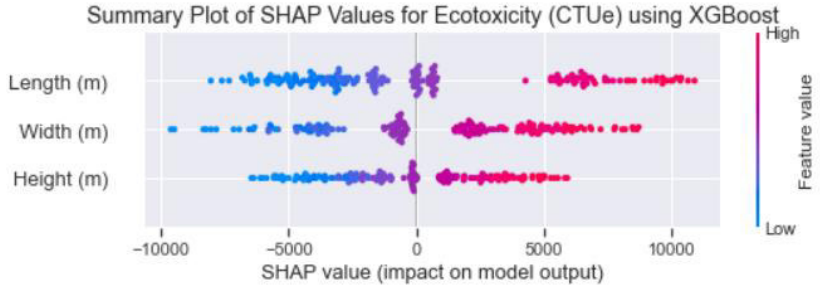
```
Model Accuracy for Fossil fuel depletion (MJ surplus): 0.9976731336338395
```




```
Model Accuracy for Ecotoxicity (CTUe): 0.9977121846450938
```




```
Model Accuracy for Ecotoxicity (CTUe): 0.9977121846450938
```




```
Model Accuracy for Smog (kg O3 eq): 0.9977121792754181
```

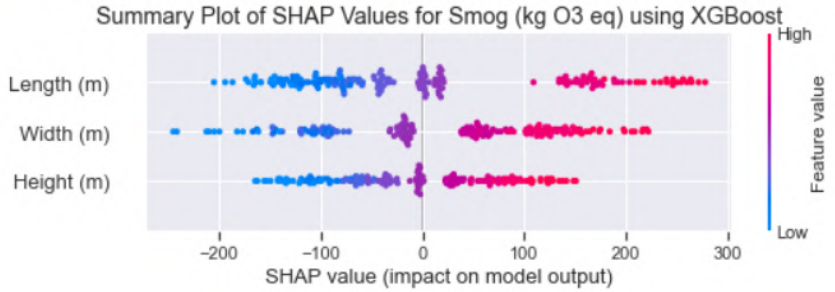


Diagram 4-25: Heatmap- Pearson correlation (Cube)

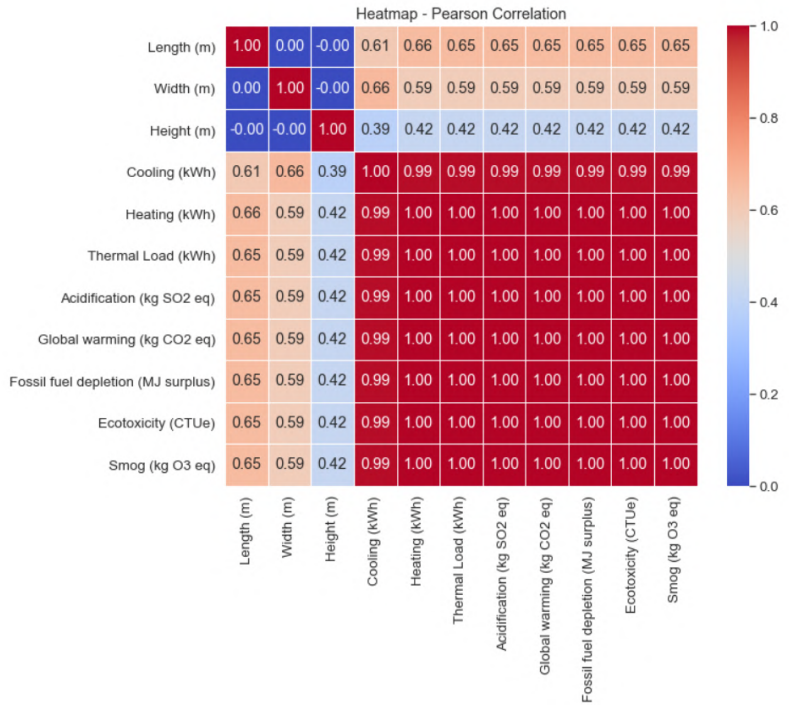


Diagram 4-26: Heatmap-Spearman Correlation

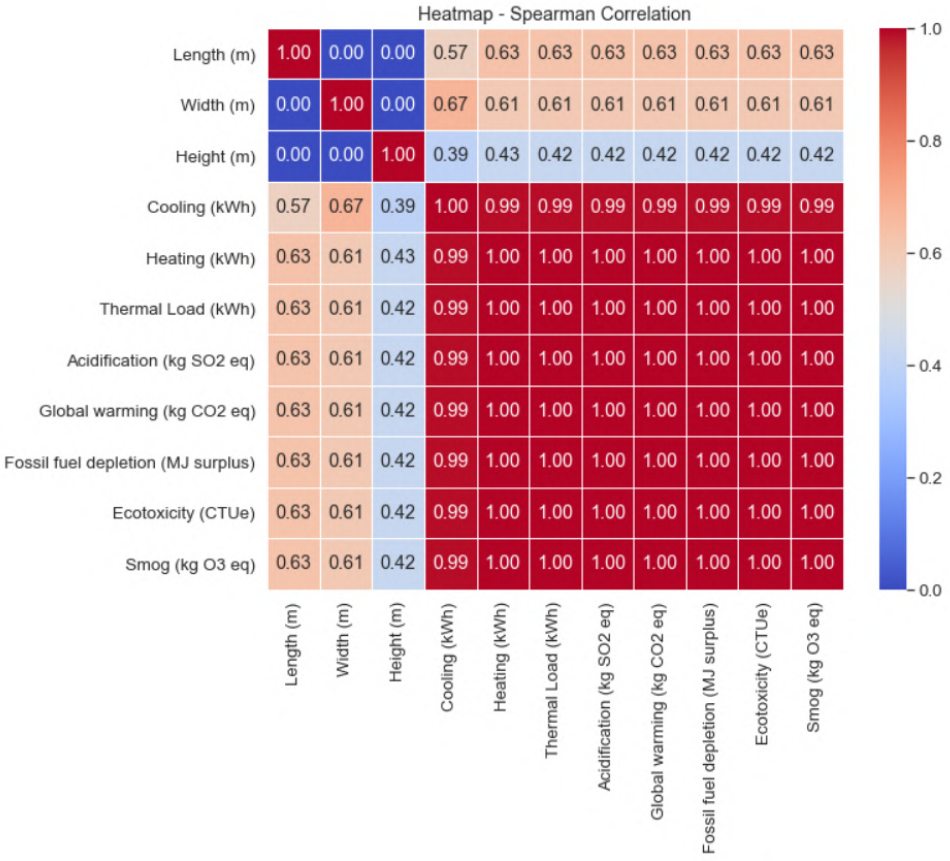


Diagram 4-27: Relative Importance of features for each goal (Cube)

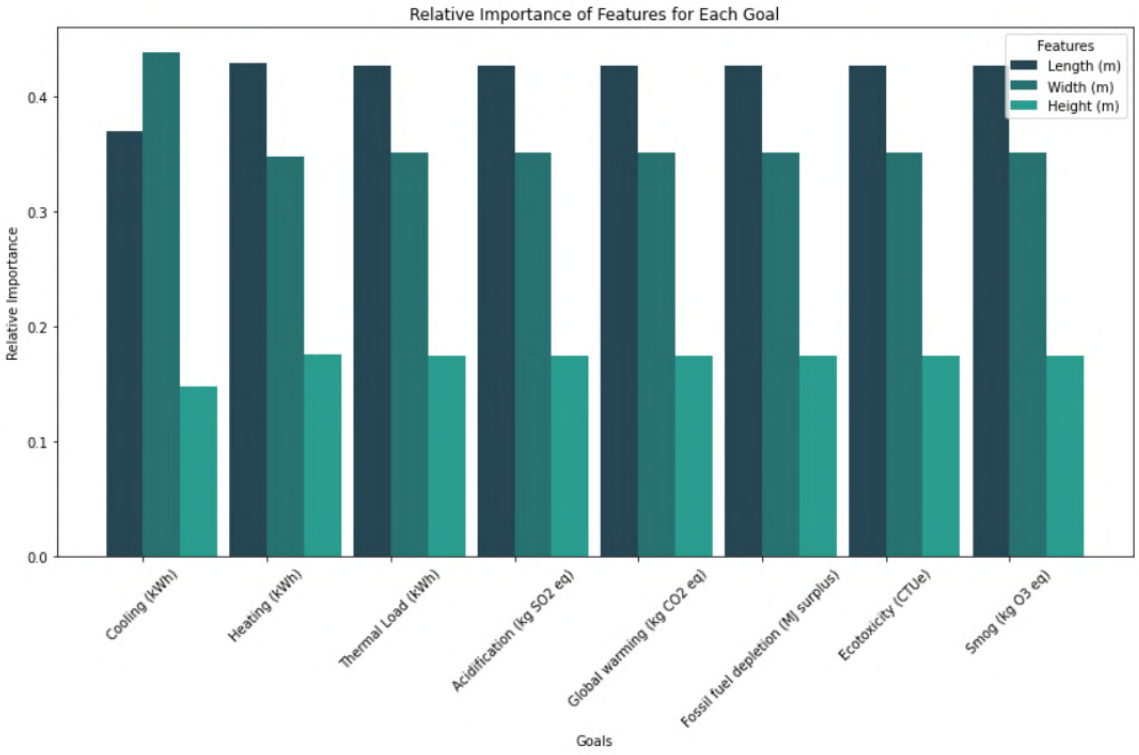


Diagram 4-28: The methodology of section 2

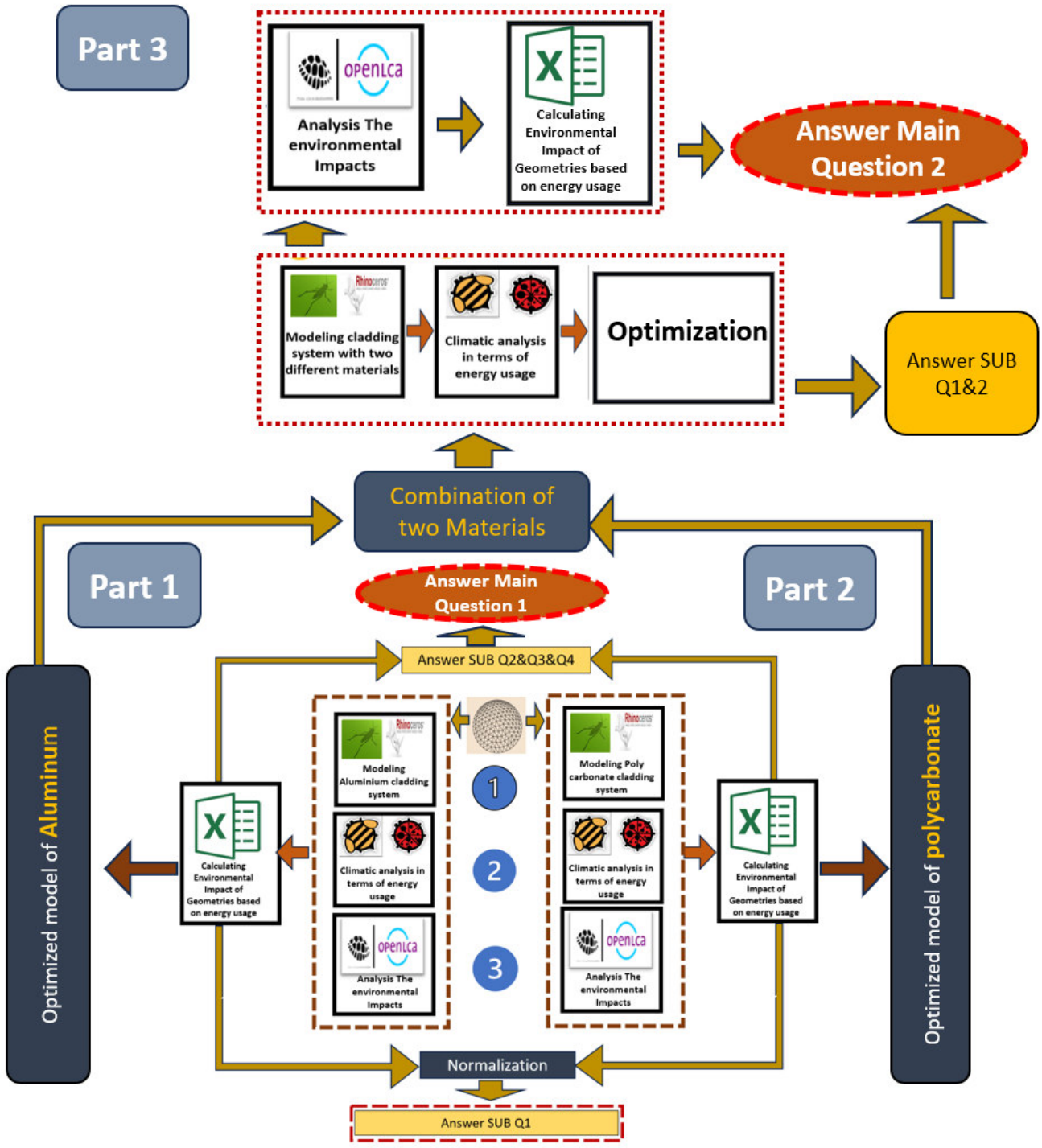


Diagram 4-29 : LCA interpretation of Klazip system

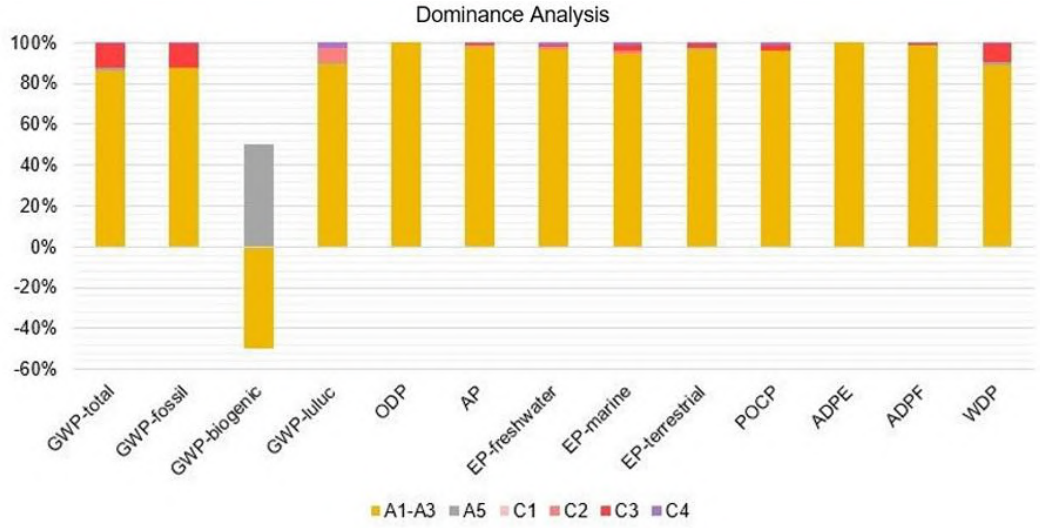


Diagram 4-30: Visualization of Table 4-13

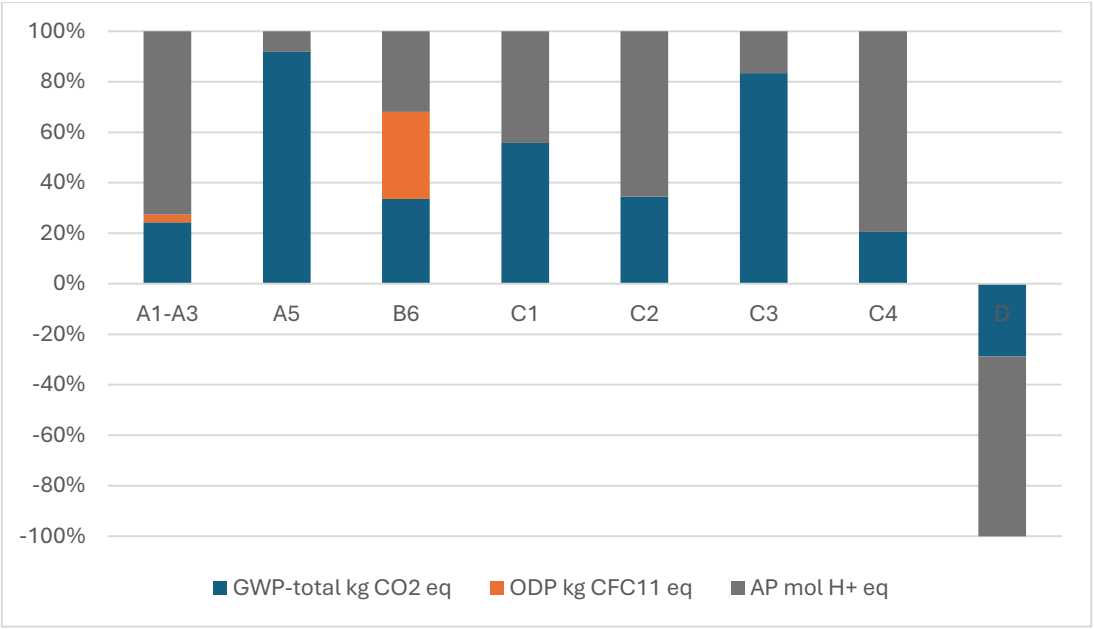
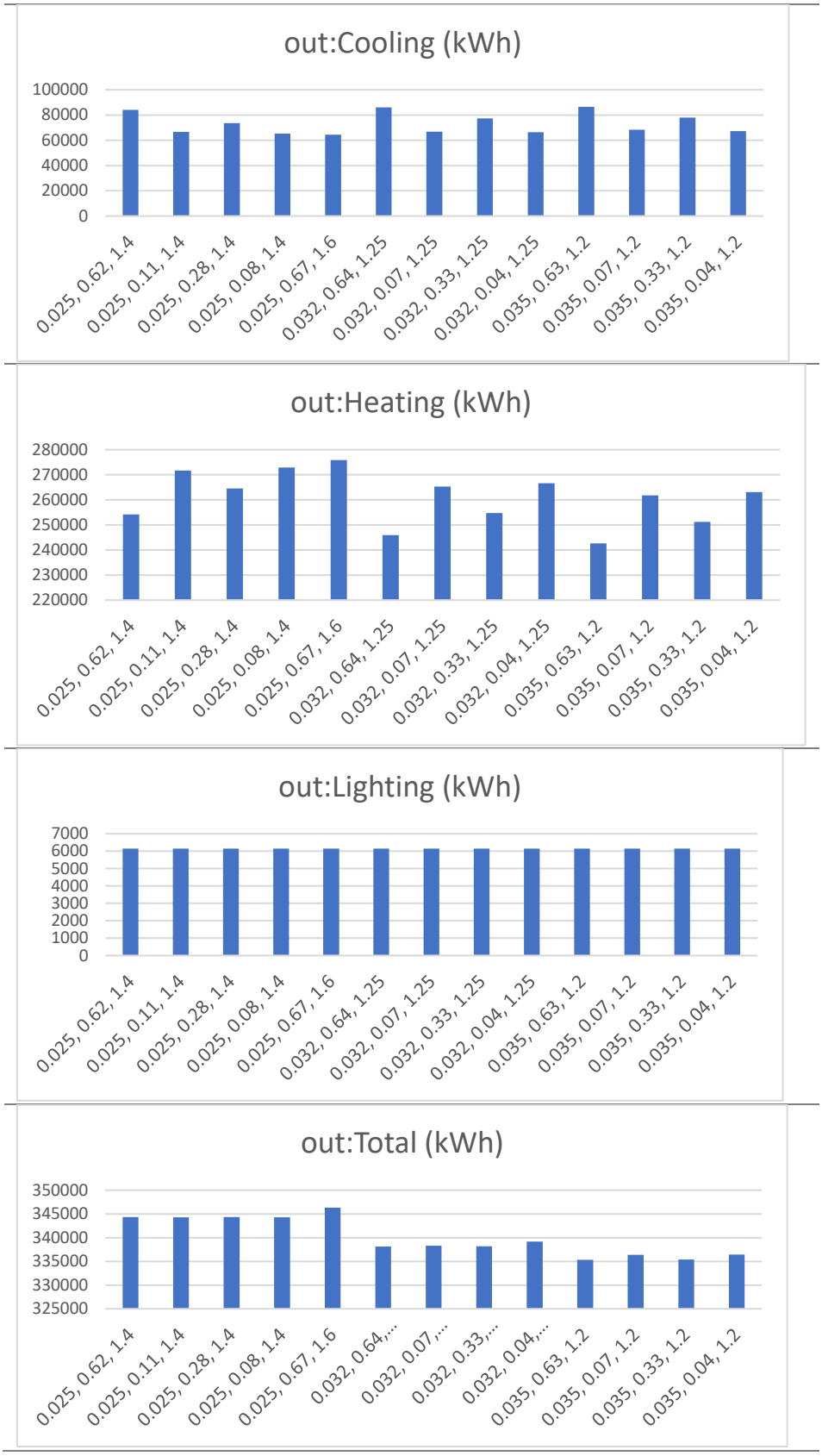


Diagram 4-31: Impact of Varied Polycarbonate Features on Building Energy Consumption



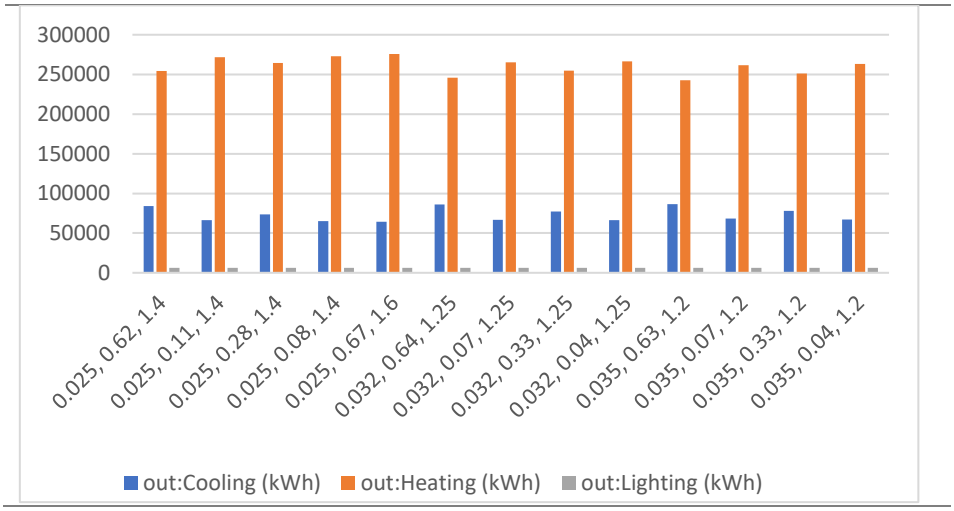
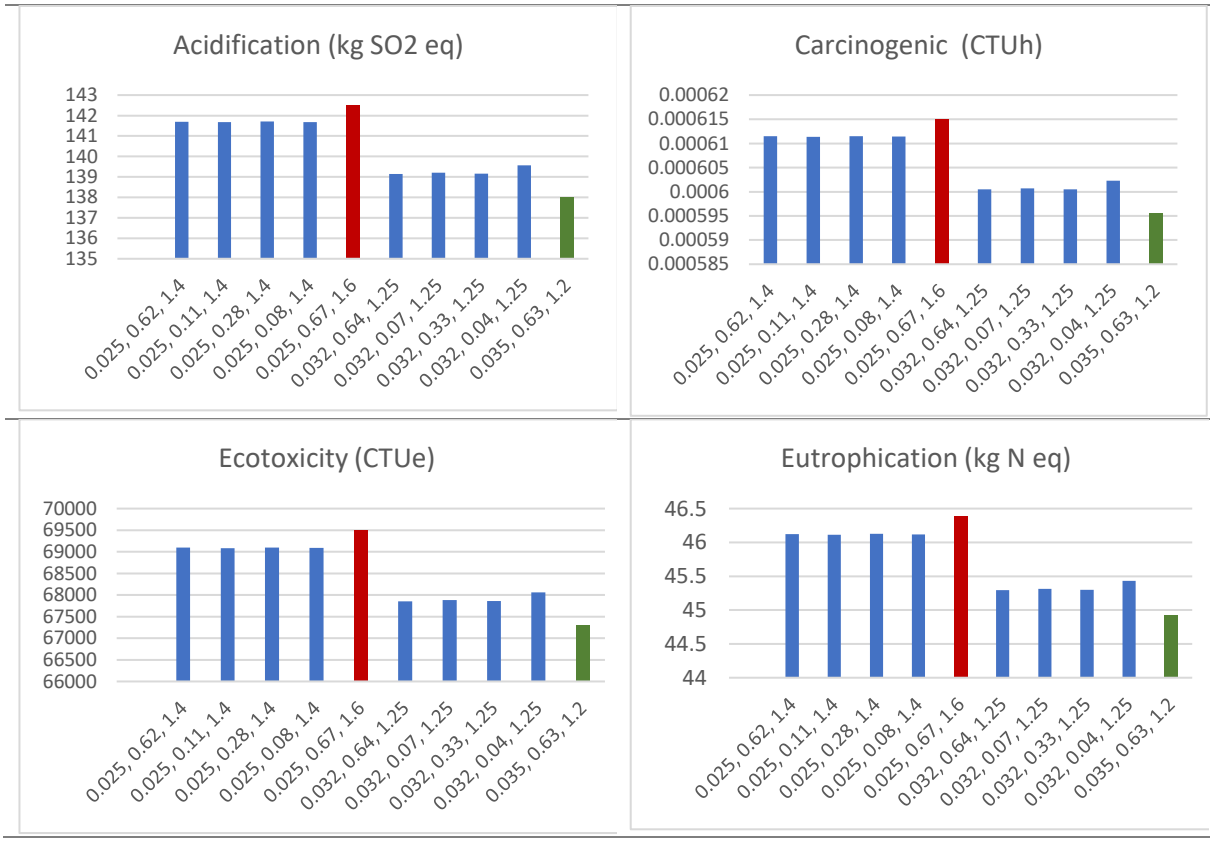


Diagram 4-32: Impact of Varied Polycarbonate Features on Building environmental impact on B6



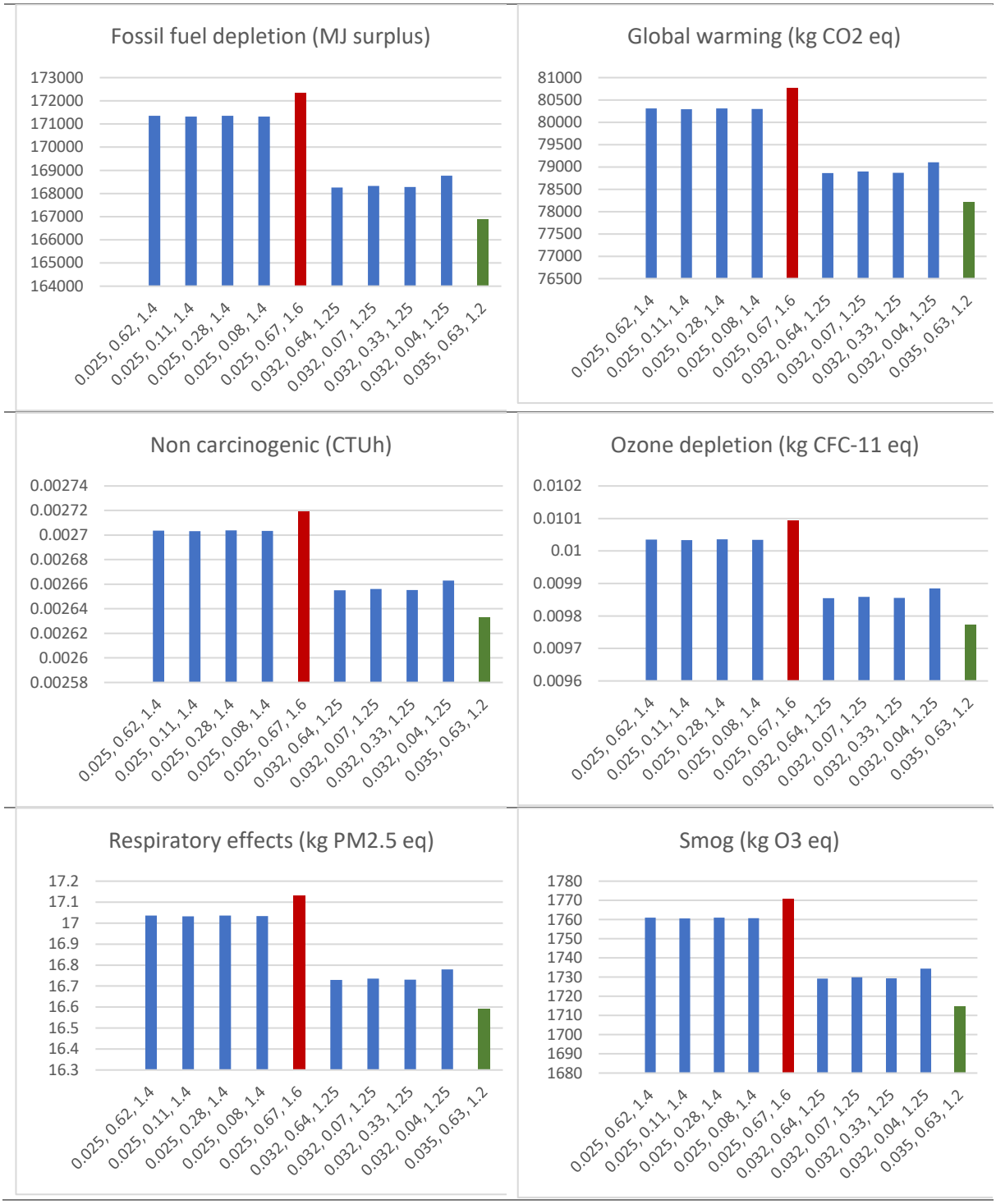

Fossil fuel depletion (MJ surplus)
173000
172000
171000
170000
169000
168000
167000
166000
165000
164000
0.025, 0.62, 1.4
0.025, 0.11, 1.4
0.025, 0.28, 1.4
0.025, 0.08, 1.4
0.025, 0.67, 1.6
0.032, 0.64, 1.25
0.032, 0.07, 1.25
0.032, 0.33, 1.25
0.032, 0.04, 1.25
0.035, 0.63, 1.2
Global warming (kg CO2 eq)
81000
80500
80000
79500
79000
78500
78000
77500
77000
76500
0.025, 0.62, 1.4
0.025, 0.11, 1.4
0.025, 0.28, 1.4
0.025, 0.08, 1.4
0.025, 0.67, 1.6
0.032, 0.64, 1.25
0.032, 0.07, 1.25
0.032, 0.33, 1.25
0.032, 0.04, 1.25
0.035, 0.63, 1.2
Non carcinogenic (CTUh)
0.00274
0.00272
0.0027
0.00268
0.00266
0.00264
0.00262
0.0026
0.00258
0.025, 0.62, 1.4
0.025, 0.11, 1.4
0.025, 0.28, 1.4
0.025, 0.08, 1.4
0.025, 0.67, 1.6
0.032, 0.64, 1.25
0.032, 0.07, 1.25
0.032, 0.33, 1.25
0.032, 0.04, 1.25
0.035, 0.63, 1.2
Ozone depletion (kg CFC-11 eq)
0.0102
0.0101
0.01
0.0099
0.0098
0.0097
0.0096
0.025, 0.62, 1.4
0.025, 0.11, 1.4
0.025, 0.28, 1.4
0.025, 0.08, 1.4
0.025, 0.67, 1.6
0.032, 0.64, 1.25
0.032, 0.07, 1.25
0.032, 0.33, 1.25
0.032, 0.04, 1.25
0.035, 0.63, 1.2
Respiratory effects (kg PM2.5 eq)
17.2
17.1
17
16.9
16.8
16.7
16.6
16.5
16.4
16.3
0.025, 0.62, 1.4
0.025, 0.11, 1.4
0.025, 0.28, 1.4
0.025, 0.08, 1.4
0.025, 0.67, 1.6
0.032, 0.64, 1.25
0.032, 0.07, 1.25
0.032, 0.33, 1.25
0.032, 0.04, 1.25
0.035, 0.63, 1.2
Smog (kg O3 eq)
1780
1770
1760
1750
1740
1730
1720
1710
1700
1690
1680
0.025, 0.62, 1.4
0.025, 0.11, 1.4
0.025, 0.28, 1.4
0.025, 0.08, 1.4
0.025, 0.67, 1.6
0.032, 0.64, 1.25
0.032, 0.07, 1.25
0.032, 0.33, 1.25
0.032, 0.04, 1.25
0.035, 0.63, 1.2

Diagram 4-33: Optimization wallacei data by design explorer.

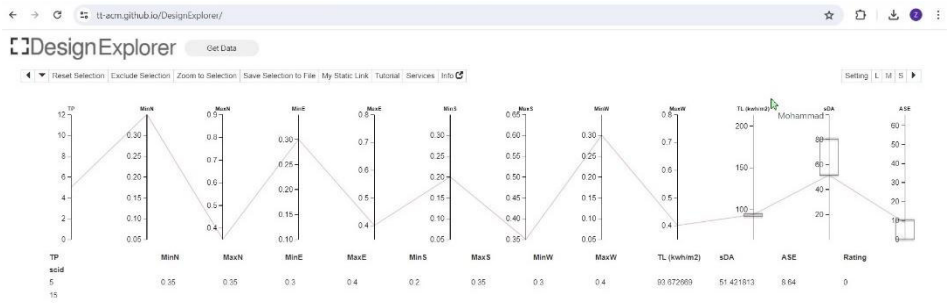


Diagram 4-34: optimization all data output from ladybug



Chapter 5

Diagram 5-1: comparison different geometries.

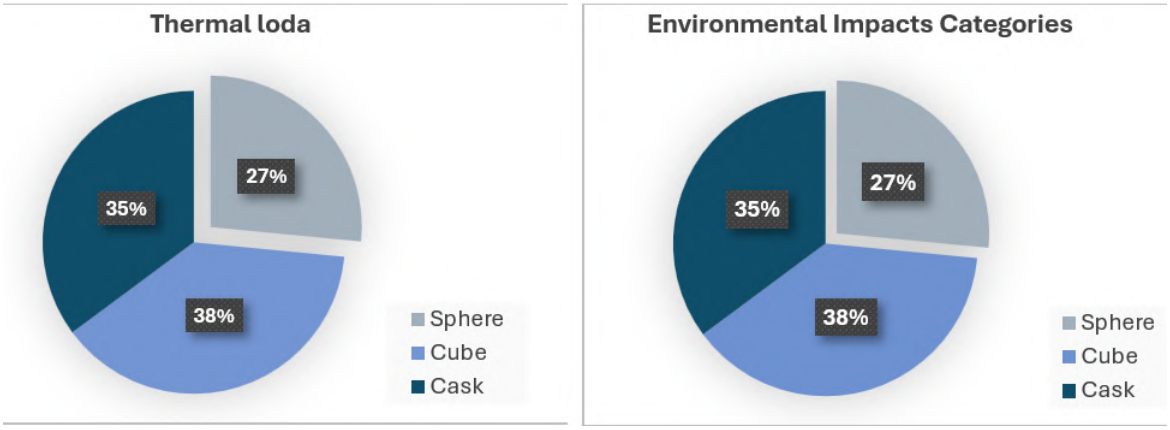


Diagram 5-2: comparison Heating and Cooling energy usage

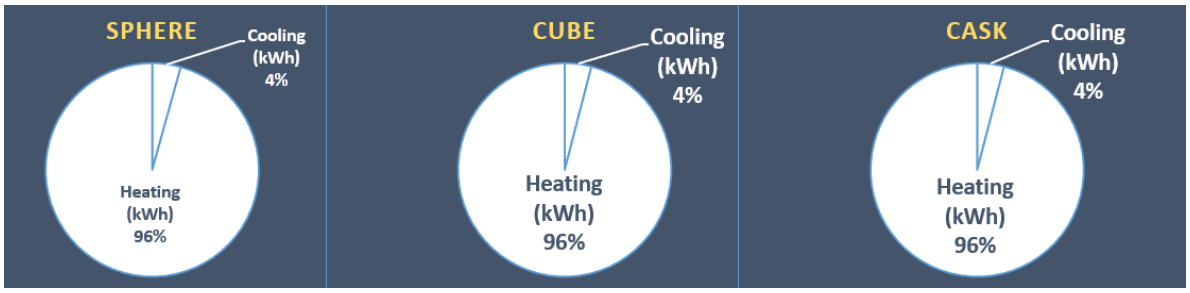


Diagram 5-3: comparison different environmental impact categories

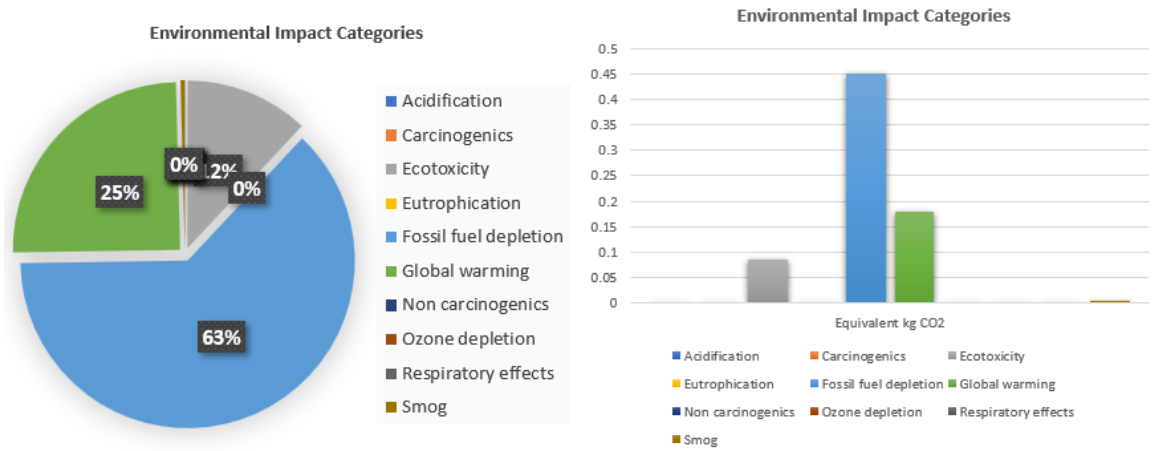


Diagram 5-4: Comparison Polycarbonate and Aluminum cladding system

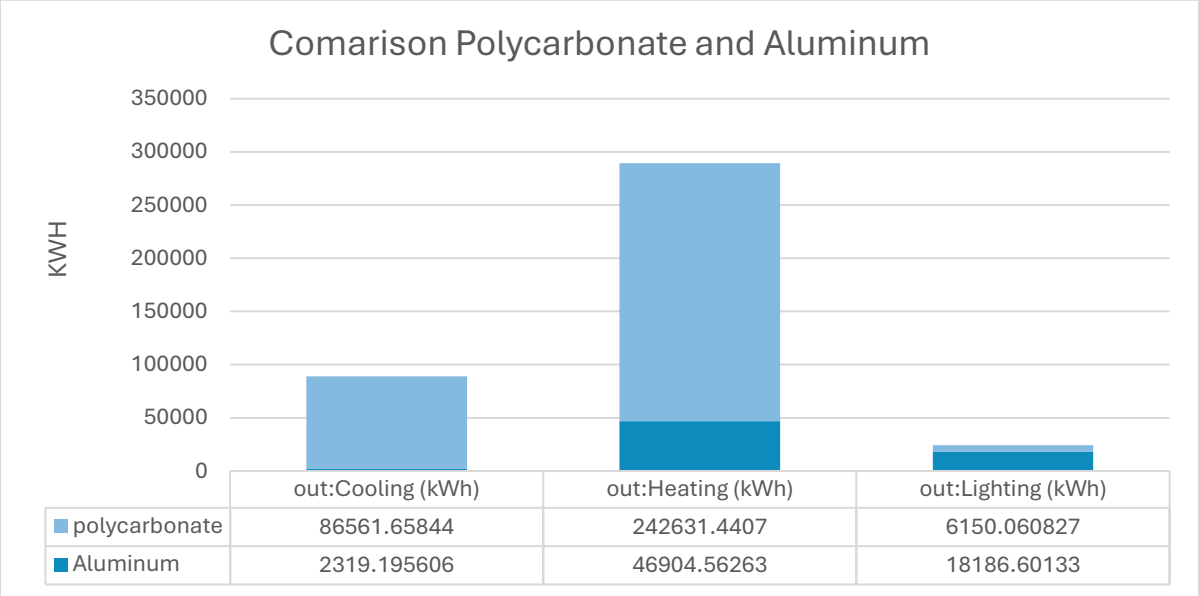


Diagram 5-5: Comparison the impact of lighting, heating and cooling energy usage

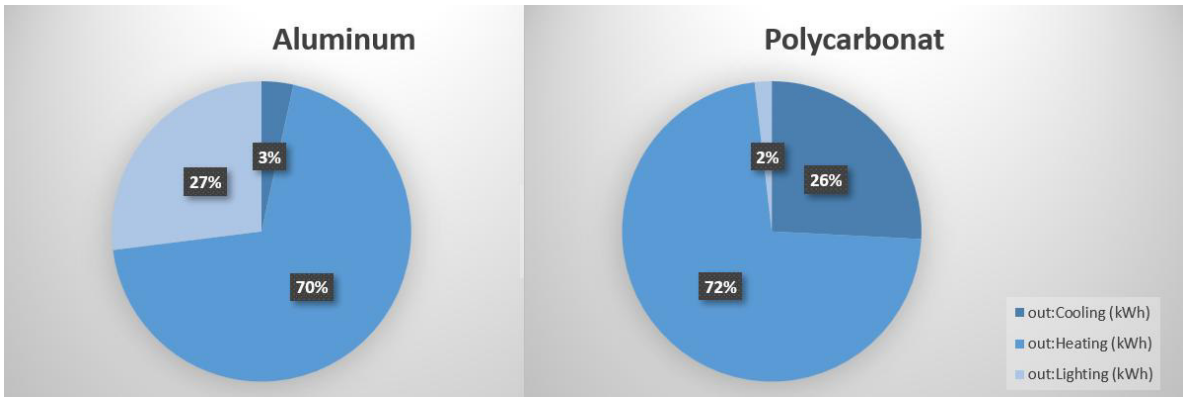
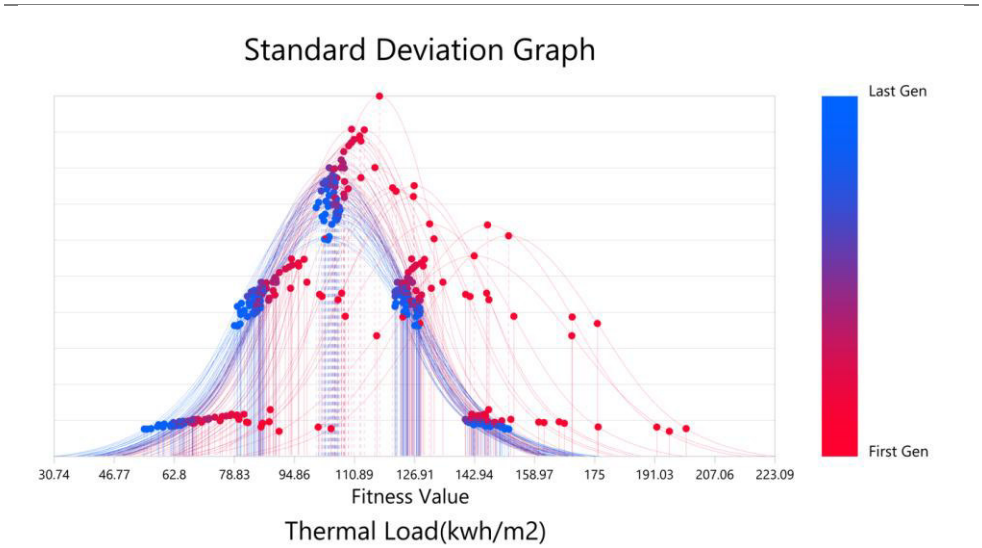
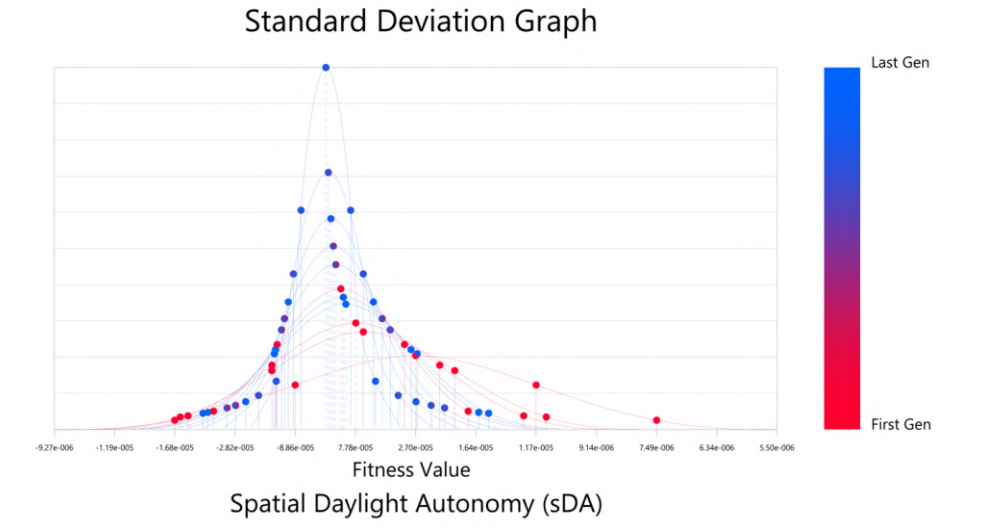


Diagram 5-6: Standard Deviation Graph





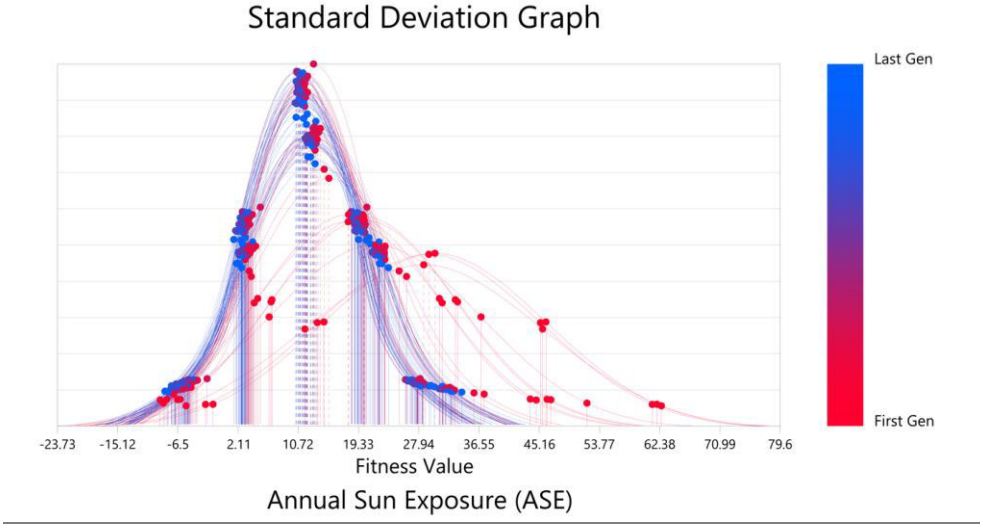
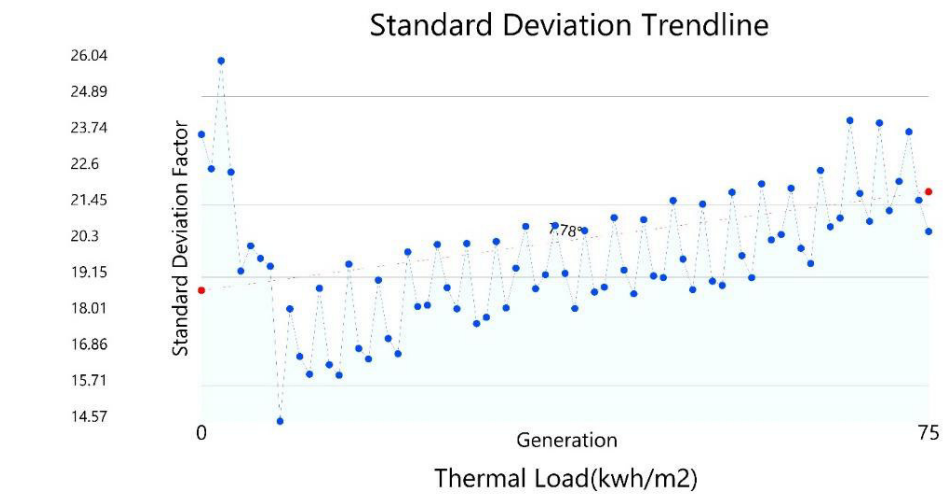
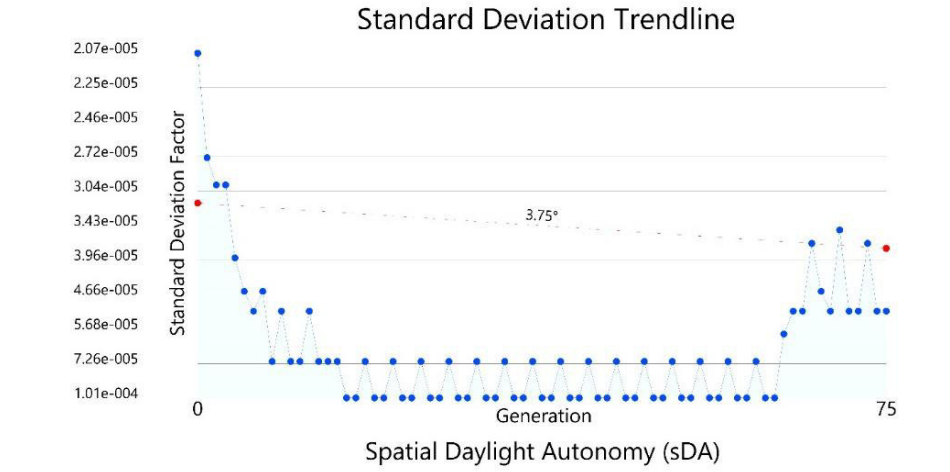


Diagram 5-7: Standard Deviation Trendline





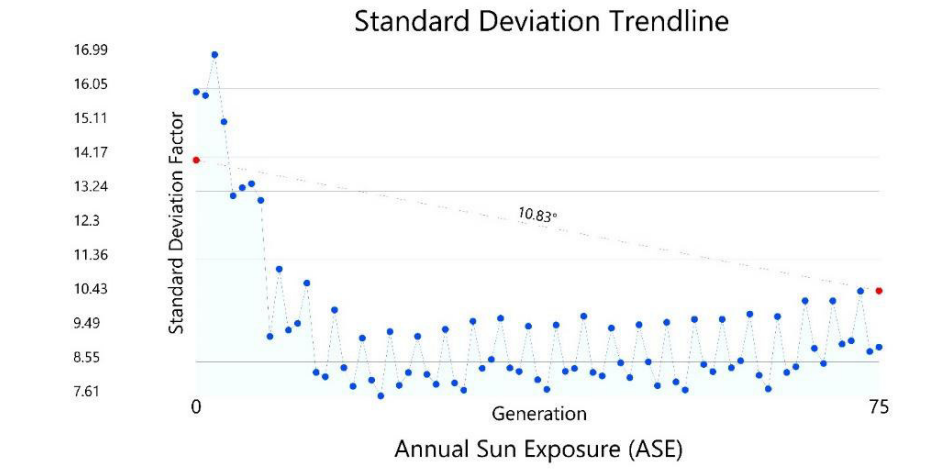
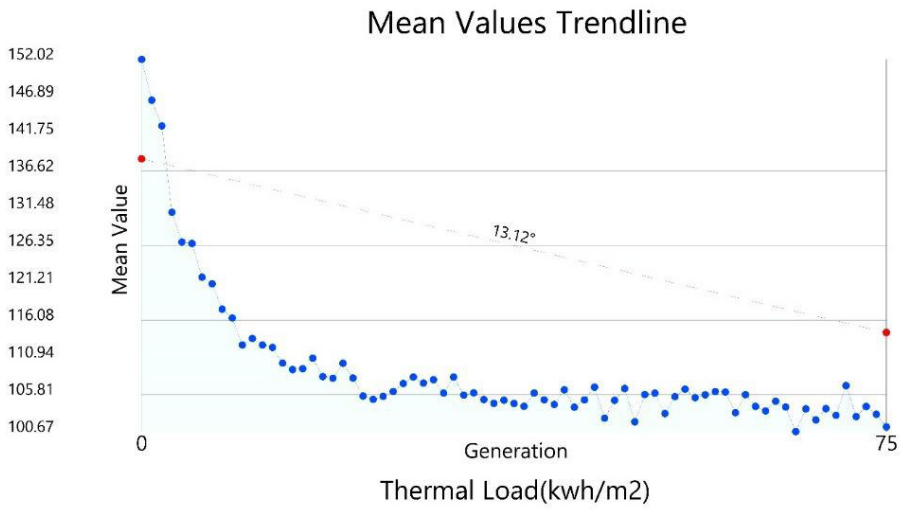


Diagram 5-8: Mean Values Trendline



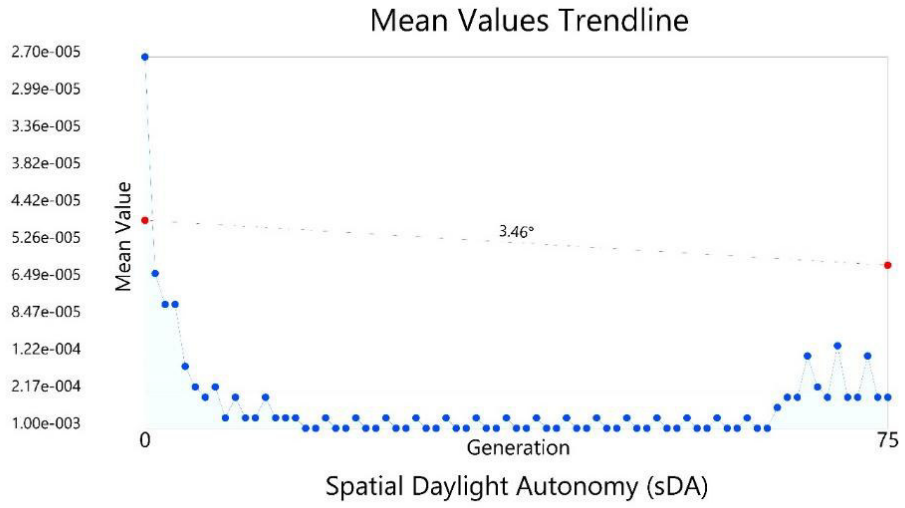
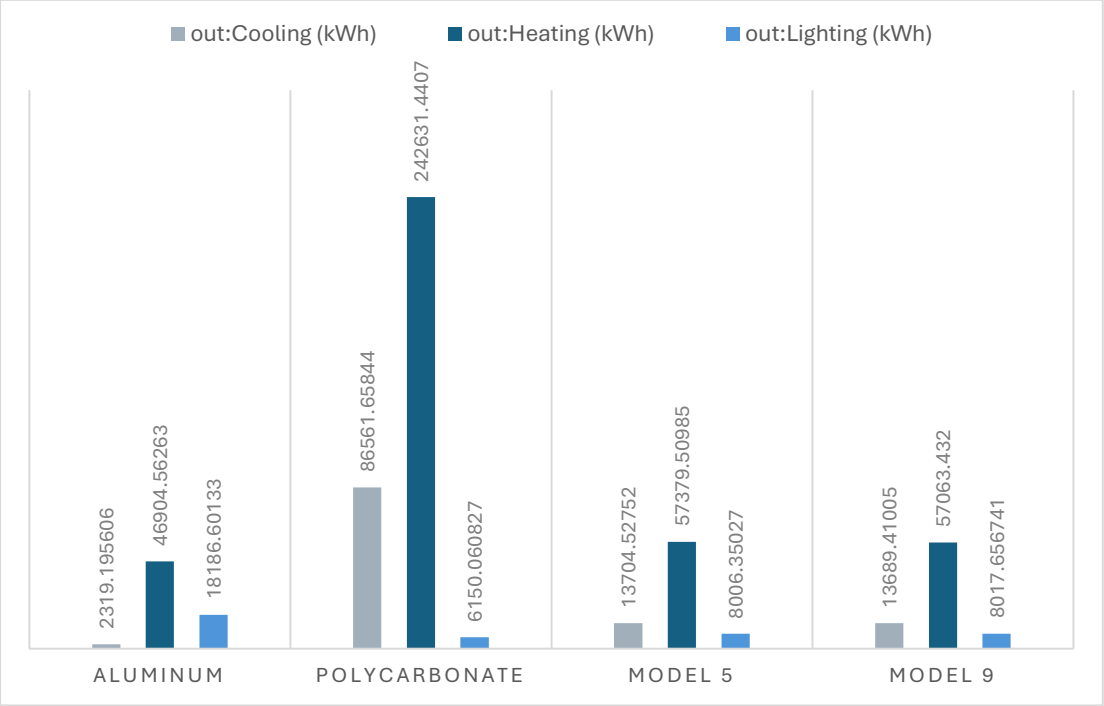


Diagram 5-9: Comparison different cladding systems



Appendix D

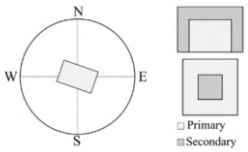
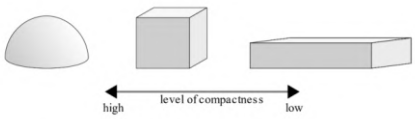
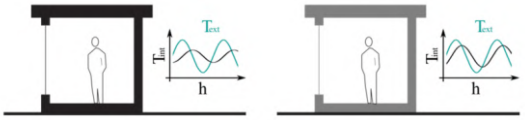
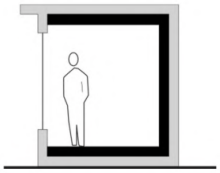
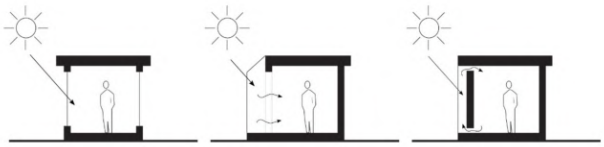
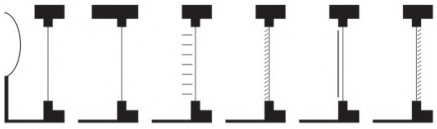
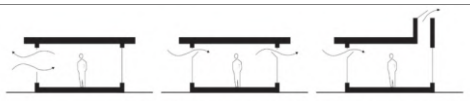
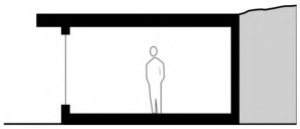
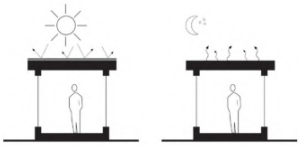
Chapter 2

Table 2-1: summary of the timeline of architectural paradigms, combine refences

Paradigm	Years	Influencer	Key concept	Example
Early Bioclimatic Architecture	1908-1940	Richard Neutra	Utilization of local climate and environmental conditions to influence building design.	Lovell Health House (1929) by Richard Neutra
Mid-Century Modernism and Environmental Awareness	1940-1970	Frank Lloyd Wright	integration of modernist architecture with natural surroundings.	Fallingwater (1935) by Frank Lloyd Wright.
Energy Crisis and Sustainable Design	1970-1980	The global energy crisis, driving a focus on solar energy and efficiency	Energy efficiency and sustainable materials due to the energy crisis	The Solar House (1973) by University of Delaware
Green Architecture Movement	1980-2000	Ken Yeang, for pioneering bioclimatic skyscraper design	Eco-friendly materials, energy efficiency, and low environmental impact.	Menara Mesiniaga (1992) by Ken Yeang.
LEED Certification and Holistic Sustainability	2000-2010	U.S. Green Building Council, for establishing LEED certification.	Widespread adoption of LEED standards, focusing on holistic sustainable building practices.	California Academy of Sciences (2008) by Renzo Piano.
Smart Green Design and Urban Sustainability	2010-2016	The regenerative design movement, pushing beyond sustainability towards restoring and improving ecosystems.	Buildings that contribute positively to the environment, beyond sustainability.	The Sustainability Pavilion for Expo 2020 Dubai. By Grimshaw Architects.
Regenerative Design	2016 so far	Lyle, Braungart, Benyus	Restore, renew, or revitalize their own sources of energy and materials, creating sustainable designs that integrate with the natural environment	Bullitt Center in Seattle (2013), Washington by the Miller Hull

[1],[2],[3],[4],[5],[6] with editing

Table 2-2: Passive tactics, (Reference:(Bugenings and Kamari 2022))

Orientation and Space Zoning	 -
"Building massing", "building volume", "compactness"	
Thermal Mass	
Thermal Insulation	
Direct and Indirect Solar Gains	
Glazing	-
Sunspaces, also called winter gardens	-
Solar/Trombe Wall	-
Solar Shading, FLTR vegetation, overhang, fixed horizontal slats, external venetian blind, external screen and internal venetian blind	 -
Convective Heat Exchange	 - Figure 8. Natural ventilation—single-sided ventilation (**left**), cross ventilation (**middle**) and stack ventilation (**right**).
Conductive Heat Exchange	
Radiative Heat Exchange	

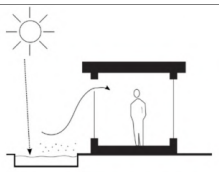
Evaporative Heat Exchange	

Table 2-3: categories of paradigms base on Nature solution approaches (Reference: Author)

Paradigms	**Decrease Negative Impact by**					**Effectiveness**	
Approach	Discovery	Harmony	Energy efficiency	Resource efficiency	Neutrality	Resiliency	Recovery
Ideology	Bioclimatic architecture	Environmental architecture	Energy conscious architecture	sustainable architecture	Green architecture	carbon neutral architecture or High performance	Regenerative architecture
Nature-derived	*	*	*	*	*	*	*
Nature-inspired	-	-	-	-	*	*	*
Nature-Based	-	-	-	-	-	-	*

Table 2-4: The history of Geometry RoI in Architectural paradigm

Architectural Paradigm	Years	Role of Geometry
Bioclimatic architecture	1908-1968	Geometry is utilized to harness climatic resources for thermal comfort, emphasizing sun paths and wind patterns for passive heating and cooling.
Environmental architecture	1969-1972	Geometry serves to minimize ecological disruption, often employing forms that reflect and integrate into the natural surroundings.
Energy conscious architecture	1973-1983	Geometry is employed to reduce energy consumption, focusing on optimizing building forms for energy efficiency and light maximization.
Sustainable architecture	1984-1993	Sustainable architecture leverages geometric design to achieve a balance between environmental responsibility, resource efficiency, and the wellbeing of occupants.
Green architecture	1993-2006	Green architecture incorporates geometric principles to reduce the carbon footprint of buildings, often including the use of renewable energy systems and sustainable materials.
Carbon neutral architecture	2006-2015	Carbon neutral architecture aims for a net-zero carbon footprint, where geometry is applied to maximize renewable energy generation and minimize energy needs.
Regenerative architecture	2016-Future	Regenerative architecture extends beyond sustainability, with geometry playing a role in creating spaces that contribute positively to their environment, aiming for a net-positive impact.

Table 2-5: the software comparison in interoperability, results, functions (Reference: T. Han et al. 2018)

	Software		Interoperability			Simulation Results					Functions				Available in the Early Stage
			Design Tool	Simulation Engine	Interoperability	Energy	Thermal	Daylighting	Air Quality	LCC	Carbon Emission	Cloud	UA/SA/PA	Optimization	
plugin	OpenStudio		SketchUp	E+ Radiance	File exchange	√	√	√	√	√			√	√	☆
	HTB2		SketchUp	Own	File exchange	√					√		√		★★
	Sefaira		SketchUp Revit	E+	Run-time	√	√	√				√	√	√	★★
	IES VE		Own Revit SketchUp	Own	File exchange	√	√	√	√	√					★
	Green Building Studio		Revit	DOE2	File exchange	√		√			√	√			★★
	Grasshopper	Honeybee and Ladybug	Rhino	E+/OpenStudio Radiance/DAYSIM	File exchange	√	√	√						√	★
		IEC bear	Rhino	Viper DIVA	File exchange	√	√	√						√	★
Independent tool	DesignBuilder		Own	E+	File exchange	√	√	√	√	√	√	√	√	√	★
	jEPlus (jESS)		Own	E+	Run-time	√						√	√	√	☆
	N++		Own	E+	File exchange	√	√		√			√			☆
	Virtual Design Studio		Own	E+	File exchange	√	√		√					√	★
	ZEBO		None	E+	File exchange	√	√						√		★★
	Riuska		Own	DOE2	File exchange	√	√		√						☆
	iDbuild		Own	BC/ LC	Standalone	√	√	√	√				√		★
	NewFacades		text	E+	File exchange	√		√							★★
	mkSchedule		SketchUp	E+ Radiance	File exchange	√		√							★★
	MIT advisor		text	Own	File exchange	√	√	√		√		√			★★

Table2-6: Comparison of basic characteristics

	DOE-2	eQUEST	EnergyPlus	ESP-r	DeST
Import CAD drawing		√	√	√	
Changeable time step		√	√	√	
Export CAD drawing			√	√	
Output report		√	√	√	√

Table 2-7 :Comparison of calculation capability

	DOE-2	eQUEST	EnergyPlus	ESP-r	DeST
Room heat balance calculation		√	√	√	√
Humidity calculation		√	√		√
Heat comfort calculation			√	√	
Nature ventilation calculation		√	√	√	√
Sunlight analysis	√	√	√	√	
Renewable energy calculation		√	√	√	

Table 2-8: Comparison of compatibility

	DOE-2	eQUEST	EnergyPlus	ESP-r	DeST
Water cycle calculation		√	√		√
Wind cycle calculation					
Greenhouse gas	√	√	√	√	
Connection with other software			√	√	√

Table 2-9: Comparison of features of various simulation software tools (Reference:Sousan,2012)

	Energy Plus	ESP-r	IDA ICE	IES	TRNSYS
Simulation Solution					
Simulation of loads, systems and solutions	*	*	*	*	*
Iterative solution of nonlinear systems	*	*	*	*	*
Duration of Time Calculation					
Variable time intervals per zone for interaction of the HVAC system	*	*			
Simultaneous selection of building systems and user		*	*	*	*
Dynamic variables based in transient solutions	*	*	*		
Complete Geometric Description					
Walls, roofs and floors	*	*	*	*	*
Windows, skylights, doors and external coatings	*	*	*	*	*
Polygons with many faces	*	*	*	*	*
Imports of building from CAD programs	*	*	*	*	*
Export Geometry of Buildings for CAD software	*	*	*		
Import/Export of simulation models of programs	*	*	*	*	
Calculation of thermal balance	*	*	*	*	
Absorption/release of moisture from the building materials	*		*	*	*
Internal thermal mass	*	*	*	*	*
Human thermal comfort	*	*	*	*	*
Solar Analysis	*				*
Analysis of Isolation	*	*	*	*	*
Advanced fenestration	*	*	*	*	*
Calculations of the building in general	*	*		*	*

Surface temperatures of zones	*	*	*	*	*
Airflow through the windows	*	*		*	*
Driving surfaces	*	*	*	*	*
Heat transfer from the soil	*	*	*	*	*
Thermophysical variable			*		
Daylighting and lighting controls	*	*	*	*	
Infiltration of a zone	*	*	*	*	*
Automatic calculation of coefficients of wind pressure				*	
Natural Ventilation	*	*	*		*
Natural and mechanical ventilation				*	*
Control open of windows for natural ventilation	*	*	*		*
Air leaks in multiple zones	*	*	*		*
Renewable Energy Systems					
Solar Energy	*	*		*	*
Trombe Wall	*	*	*	*	*
Photovoltaic panels	*	*		*	*
Hydrogen Systems		*			*
Wind Energy		*			*
Electrical Systems and Equipment					
Energy Production through R.E.	*	*			*
Distribution and management of electric power loads	*	*			*
Electricity generators	*				*
Network connection	*	*			*
HVAC Systems					
HVAC idealized	*	*	*	*	*
Possible configuration of HVAC systems	*	*	*	*	*
Repetitions cycle air	*	*	*	*	*
distribution systems	*	*	*	*	*
Modeling CO_2			*	*	*
Each distribution of air per area	*	*	*	*	*
Forced air unit per zone	*	*	*	*	*
equipment Unit	*	*		*	*

Chapter 3

Table 3-2: summarizes Important elements of the LCA's history, (Hauschild et al., 2018)&LCa class,winter2023

Event	Year	Note
The (perhaps) *first* LCA-oriented study was presented on energy requirements for the production of chemical intermediates and products	1963	World Energy Conference, Harold Smith
Coca Cola commissions its *first* study comparing beverage containers	1969	Not public
The methodological foundation for environmentally extended input/output analysis is made	1970	Leontief (1970)
Publication of the *first* public and peer-reviewed LCA study "Resource and Environmental Profile Analysis of Nine Beverage Container Alternatives", commissioned by the US EPA	1974	EPA (1974)
First impact assessment method based on critical volumes introduced	1984	BUS (1984)
The *first* widely used commercial LCA software, GaBi, was released in its *first* version	1989	Thinkstep (2016)
SimaPro, another widely used commercial LCA software, was released in its *first* version	1990	PRé (2016)
The term "life cycle assessment" was coined	1990	SETAC (1991)
Emergence of a number of LCI databases managed by different institutions	Early1990s	
First environmental theme-oriented impact assessment methodology, CML92	1992	Heijungs et al. (1992)
SETAC Code of Practice published in effort to harmonise LCA framework, terminology and methodology	1993	SETAC (1993b)
The academic journal fully dedicated to LCA, The International Journal of Life Cycle Assessment, was born	1996	
ISO 14040 standard on LCA principles and framework released	1997	ISO 14040
ISO 14041 standard on goal and scope de*f*inition released	1998	ISO 14041
Damage-oriented methodology Eco-indicator 99 emerges	1999	Goedkoop and Spriensma(2000)
ISO 14042 standard on life cycle impact assessment released	2000	ISO 14042
ISO 14043 standard on life cycle interpretation released	2000	ISO 14043
UNEP/SETAC Life Cycle Initiative launched	2002	
The LCI database ecoinvent version 1.01 is released	2003	Ecoinvent (2016)
Establishing of a general methodological framework and guideless for LCA through ISO 14040 and ISO 14044	2006	
A framework for Life Cycle Sustainability Analysis was proposed	2008	Klöpffer (2008)
ILCD handbook published	2010	EC (2010)
further EU standardization in International LCA Data (ILCD) System	2012	
PEF and OEF guidelines published	2012-2013	ISO 14046
,LCA standardization for buildings&construction	2013-2015	LEEDv4 (US) ,BREEAM (UK), EN15643 (EU)
standardizes process for Produce Category Rules	2017	PCR (1402x)

Table 3.4: Comparison of life cycle assessment tools,(Reference: ecochain.com)

	Eco chain Mobius	Ecochain Helix	GaBi	Oneclicklca	openLCA	SimaPro
Ease of use	Easy	Moderate	Moderate to difficult	Moderate to difficult	Moderate to difficult	Moderate to difficult
Free Trial	Yes, 14-day free trial	No, but demo is available	Yes, 30-day free trial	Yes, 14-day free trial	N.A. Free software	No, but you can download a demo version
Cloud-based Application	Yes	Yes	No, download only	Yes	No, download only	No, download only
URL	ecochain.com/mobius	ecochain.com/helix	www.gabi-software.com	www.oneclicklca.com/	www.openlca.org/	www.simapro.com

Table 3.5: Tools and database for construction sector

Tools & Database		Includes LCI database	LCA tools *specifically* for building materials/assemblies	Whole-building LCA tools
GaBi	GaBi	*		
BEES	BEES	*	*	
FEDERAL LCA COMMONS	USLCI	*		
Athena Sustainable Materials Institute	Athena IE for Buildings/ Eco-Calculator	*	*	*
NIST National Institute of Standards and Technology U.S. Department of Commerce	NIST BIRDS			*
One Click LCA	One-click LCA			*
tally	Tally (http://choosetally.com/tutorials/)			*
ecoinvent	Ecoinvnet	*		
openLCA	Open ICA	*	*	*
	Kaleidoscope Tool (Online access)		*	

Table 3-6: Summary of green building certification, (Reference: www. wbdg.org)

Building Rating or Certification System	Single- or Multi-Attribute	Type of Standard or Certification	Managing Organization	Issues / Areas of Focus
Building Research Establishment Environmental Assessment Method (BREEAM)	Multi-Attribute	Green building rating and certification system through on-site independent third-party verification for: • New Construction • In-Use • Refurbishment & Fit Out • Communities Infrastructure	BRE Global	Performance in: • Energy • Health & Well-being • Transport • Water • Materials • Waste • Land Use & Ecology • Management • Pollution No prerequisites for In-Use
Leadership in Energy and Environmental Design (LEED)	Multi-Attribute	Green building rating and certification system through independent third-party verification for: • New Construction (NC) • Existing Buildings, Operations & Maintenance (EB O&M) • Commercial Interiors (CI) • Core & Shell (CS) • Schools (SCH) • Retail • Healthcare (HC) • Residential • Cities and Communities	U.S. Green Building Council	Performance in: • Sustainable Sites • Water Efficiency • Integrative Process • Location & Transporation • Energy & Atmosphere • Materials & Resources • Indoor Environmental Quality • Innovation • Regional Priority
Green Globes	Multi-Attribute	Green building guidance and assessment program for: • Existing buildings • New construction	Green Building Initiative in the U.S. BOMA Canada	Environmental assessment areas to earn credits in: • Energy • Indoor Environment • Site • Water Efficiency • Materials • Project Management No prerequisites
Living Building Challenge	Multi-Attribute	Performance-based standard, and certification program for: • Landscape and infrastructure projects • Partial renovations and	International Living Future Institute	Performance areas include: • Place • Water • Energy • Materials • Health & Happiness • Equity

		complete building renewals • New building construction • Neighborhood, campus and community design		• Beauty All areas are requirements.
Passive House Institute US	Multi-Attribute	Performance based passive building standard: • Third-party RESNET approved quality assurance/quality control • Earns U.S. DOE Zero Energy Ready Home status • Includes HERS rating	Passive House Institute US	Any type of building. New focus areas include: • air tightness requirements • source energy limit • space conditioning criteria • net zero energy
SITES	Multi-Attribute	Third-party verified rating system for development projects located on sites with or without buildings including: • Open spaces • Streetscapes and plazas • Commercial • Residential • Educational/Institutional	Administered by GBCI	Performance criteria in the areas of: • Site Context • Water • Soil & Vegetation • Human Health & Well-being • Materials Selection, and more
WELL Building Standard	Multi-Attribute	Performance based standard and certification program for: • New and Existing Buildings • New and Existing Interiors • Core and Shell Retail • Retail • Education Facilities • Restaurant • Commercial Kitchen • Multifamily Residential	Administered by the International WELL Building Institute™ (IWBI)	Measures attributes of buildings that impact occupant health by looking at ten factors: Air, Water, Nourishment, Light, Movement, Thermal Comfort, Sound, Materials, Mind, Community, and Innovation.
Fitwel	Multi-Attribute	• New Construction • Existing Buildings	Center for Active Design	Fitwel's seven health impact categories are: Impacts Surrounding Community Health, Reduces Morbidity and

				Absenteeism, Supports Social Equity for Vulnerable Populations, Instills Feelings of Well-Being, Enhances Access to Healthy Foods, Promotes Occupant Safety, and Increases Physical Activity
International Programs				
BCA Green Mark Scheme (Singapore)	Multi-Attribute	Benchmarking scheme that aims to achieve a sustainable built environment by incorporating best practices in environmental design and construction, and the adoption of green building technologies.	Building and Construction Authority (BCA)	Rates buildings according to five key criteria: • Energy efficiency • Water efficiency • Environmental protection • Indoor environmental quality, and • Other green and innovative features that contribute to better building performance.
Beam (Hong Kong)	Multi-Attribute	Comprehensive standard and supporting process covering all building types, including mixed use complexes, both new and existing to assess, improve, certify, and label the environmental performance of buildings	Business Environment Council	Performance and assessment in: • Site aspects • Material aspects • Water use • Energy use • Indoor environmental quality • Innovations and additions
CASBEE (Japan)	Multi-Attribute	Building assessment tools for • Pre-design • New Construction • Existing Building and • Renovation	JSBC (Japan Sustainable Building Consortium) and its affiliated sub-committees	Assessment areas include: • Energy efficiency • Resource efficiency • Local environment, and • Indoor environment
EDGE	Multi-Attribute	A universal standard and a certification system for residential and commercial structures.	International Finance Corporation (IFC), a member of the World Bank Group	Assessment areas include: • Energy • Water • Materials
Green Star SA (South Africa)	Multi-Attribute	Green building rating system for: • Office • Retail • Multi-unit residential	Green Building Council of South Africa administers program Independent assessors to assess and score projects	Categories assessed in: • Management • Indoor Environmental Quality • Energy • Transport • Water • Materials • Land Use & Ecology

				• Emissions • Innovation
Pearl Rating System for Estidama (UAE)	Multi-Attribute	Green building rating system for: • Community • Buildings • Villas • Temporary Villas and Buildings	Abu Dhabi Urban Planning Council	Assessment of performance in: • Integrated Development Process • Natural Systems • Livable Communities • Precious Water • Resourceful Energy • Stewarding Materials • Innovating Practice

Table 3.7: the most renowned international green building

Certification	Supported
BREEAM International	BREEAM Int'l NC 2016, BREEAM Int'l RFO 2015, BREEAM Int'l NC 2013, Commercial EU 2009, Int'l Bespoke 2010
LEED	LEED v4.1, v4, v3 (both BD+C & ID+C credits)
DGNB	DGNB Int'l, DE, DK
Level(s)	Most macro-objectives
Zero Carbon Certification & Living Building Challenge	Can be done in most carbon tools.

Chapter 4

Table 4-1: Input and output results after modeling sphere

in:Radius	in:Height	out:Thermal Load (kWh)	out:Cooling (kWh)	out:Heating (kWh)	out:Cooling (kWh/m2)	out:Heating (kWh/m2)	out:Thermal Load (kWh/m2)	out:Area (m2)	out:Volume (m3)	out:H
5.7	0.93	6949.507445	289.871688	6659.635757	2.890407	66.405447	69.295854	100.287493	377.749552	5.2545
5.7	0.82	6595.02943	279.982333	6315.047097	2.791797	62.969438	65.761236	100.287493	377.749552	4.633
5.7	0.75	6402.695557	275.190718	6127.504838	2.744018	61.099392	63.84341	100.287493	377.749552	4.2375
5.7	1	7196.283853	298.236157	6898.047695	2.973812	68.782732	71.756544	100.287493	377.749552	5.65
5.7	0.73	6340.584574	273.713552	6066.871022	2.729289	60.494792	63.224081	100.287493	377.749552	4.1245
5.7	0.79	6527.913729	279.136991	6248.776737	2.783368	62.308635	65.092003	100.287493	377.749552	4.4635
5.7	0.94	6982.486747	290.783281	6691.703465	2.899497	66.725205	69.624702	100.287493	377.749552	5.311
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
28	0.75	157166.2451	5967.990964	151198.2542	2.387108	60.477068	62.864176	2500.092345	47018.4029	21.1575
28	1	177435.7777	6539.884122	170895.8936	2.615857	68.355832	70.97169	2500.092345	47018.4029	28.21
28	0.73	156342.3039	5991.474794	150350.8291	2.396501	60.13811	62.534612	2500.092345	47018.4029	20.5933
28	0.79	160964.4442	6142.012829	154822.4314	2.456714	61.926685	64.383399	2500.092345	47018.4029	22.2859
28	0.94	172051.6662	6349.843038	165701.8232	2.539843	66.278281	68.818124	2500.092345	47018.4029	26.5174
28	0.83	164123.491	6253.141384	157870.3497	2.501164	63.145807	65.646972	2500.092345	47018.4029	23.4143
28	0.77	159415.5949	6072.719092	153342.8758	2.428998	61.334885	63.763883	2500.092345	47018.4029	21.7217
28	0.7	150065.3494	5676.04587	144389.3036	2.270334	57.753588	60.023923	2500.092345	47018.4029	19.747
28	0.93	171251.7754	6339.24358	164912.5318	2.535604	65.962576	68.49818	2500.092345	47018.4029	26.2353
28	0.71	150797.0872	5711.561922	145085.5253	2.28454	58.032067	60.316607	2500.092345	47018.4029	20.0291
28	0.7	150065.3494	5676.04587	144389.3036	2.270334	57.753588	60.023923	2500.092345	47018.4029	19.747

Table 4-2: input and output results after modeling cube

in:Length (x)	in:Width (Y)	in:Height (Z)	out:Thermal Load (kWh)	out:Cooling (kWh)	out:Heating (kWh)	out:Cooling (kWh/m2)	out:Heating (kWh/m2)	out:Thermal Load (kWh/m2)	out:Area (m2)	out:Volume (m3)
10.45	10	3.76	9010.651	363.7439	8646.907	3.480803	82.74552	86.22632	104.5	392.92
10.45	10	5.64	11218.36	453.7968	10764.57	4.342553	103.0102	107.3528	104.5	589.38
10.45	10	7.52	13456.05	545.7781	12910.27	5.222757	123.5433	128.766	104.5	785.84
10.45	10	9.4	15705.53	636.2469	15069.28	6.088487	144.2037	150.2922	104.5	982.3
10.45	10	11.28	17972.86	732.6531	17240.2	7.011034	164.978	171.9891	104.5	1178.76
10.45	10	13.16	20252.38	831.259	19421.12	7.954631	185.8481	193.8027	104.5	1375.22
10.45	10	15.04	22535.08	925.1609	21609.92	8.853214	206.7935	215.6467	104.5	1571.68
10.45	10	16.92	24822.2	1018.45	23803.75	9.74593	227.7871	237.533	104.5	1768.14
10.45	10	18.8	27114.79	1111.681	26003.11	10.6381	248.8336	259.4717	104.5	1964.6
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
49.4	49.91	13.16	182629.8	6728.834	175900.9	2.729137	71.34337	74.07251	2465.554	32446.69
49.4	49.91	15.04	193173.6	7242.721	185930.9	2.937563	75.41139	78.34896	2465.554	37081.93
49.4	49.91	16.92	203649	7590.866	196058.1	3.078767	79.5189	82.59766	2465.554	41717.17
49.4	49.91	18.8	214112.3	7871.435	206240.8	3.192562	83.64888	86.84144	2465.554	46352.42

Table 4-3: input and output results after modeling

in:Radius	in:Length (Y)	in:Height (Z)	out:Thermal Load (kWh)	out:Cooling (kWh)	out:Heating (kWh)	out:Cooling (kWh/m2)	out:Heating (kWh/m2)	out:Thermal Load (kWh/m2)	out:Area (m2)	out:Volume (m3)
5	10	1	8264.148	335.9719	7928.176	3.359719	79.28177	82.64148	100	392.6991
5	10	1.045	8329.703	188.8629	8140.84	1.888629	81.4084	83.29703	100	410.3705
5	10	1.061	8412.522	191.3434	8221.179	1.913434	82.21179	84.12522	100	416.6537
5	10	1.033	8417.13	342.3111	8074.819	3.423111	80.74819	84.1713	100	405.6582
5	10	1.081	8504.693	184.2168	8320.477	1.842168	83.20477	85.04693	100	424.5077
5	10	1.089	8572.387	203.7886	8368.598	2.037886	83.68598	85.72387	100	427.6493
5	10	1.16	8839.479	174.5891	8664.89	1.745891	86.6489	88.39479	100	455.5309
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
20	62.497	1.081	192984.8	7333.867	185650.9	2.933688	74.26394	77.19763	2499.88	42448.73
20	62.497	1.089	193339.4	7336.677	186002.7	2.934812	74.40465	77.33947	2499.88	42762.88
20	62.497	1.16	195020.9	3926.836	191094.1	1.57081	76.4413	78.01211	2499.88	45550.91
20	62.497	1.197	198929.2	3898.682	195030.5	1.559548	78.01596	79.57551	2499.88	47003.82
20	62.497	1.154	199803.8	7536.741	192267.1	3.014841	76.91052	79.92537	2499.88	45315.3
20	62.497	1.2	203630.5	7642.311	195988.1	3.057071	78.39902	81.45609	2499.88	47121.63

Table 4-4: The environmental Impact

Impact category	Reference unit	Result
Fossil fuel depletion	MJ surplus	0.497635447
Global warming	kg CO2 eq	0.233240495
Ecotoxicity	CTUe	0.200677104
Smog	kg O3 eq	0.005114277
Acidification	kg SO2 eq	0.000411533
Eutrophication	kg N eq	0.000133957
Respiratory effects	kg PM2.5 eq	4.94753E-05
Ozone depletion	kg CFC-11 eq	2.91448E-08
Non carcinogenics	CTUh	7.85226E-09
Carcinogenics	CTUh	1.7759E-09

Table 4-5: Input and output data's Sphere

in:Radius	in:Height	out:Thermal Load (kWh)	out:Area (m2)	Acidification	Carcinogenics	Ecotoxicity	Eutrophication	Fossil fuel depletion	Global warming	Non carcinogenics	Ozone depletion	Respiratory effects	Smog
5.65	0.7	6234.639	100.2875	2.565759	1.11E-05	1251.15	0.83517	3102.577	1454.17	4.90E-05	0.000182	0.30846	31.886
5.65	0.7	6234.639	100.2875	2.565759	1.11E-05	1251.15	0.83517	3102.577	1454.17	4.90E-05	0.000182	0.30846	31.886
5.65	0.71	6264.742	100.2875	2.578148	1.11E-05	1257.19	0.83921	3117.558	1461.19	4.92E-05	0.000183	0.30995	32.04
5.65	0.73	6340.585	100.2875	2.609359	1.13E-05	1272.41	0.84937	3155.3	1478.88	4.98E-05	0.000185	0.3137	32.428
5.65	0.75	6402.696	100.2875	2.63492	1.14E-05	1284.87	0.85769	3186.208	1493.37	5.03E-05	0.000187	0.31678	32.745
5.65	0.77	6465.597	100.2875	2.660806	1.15E-05	1297.5	0.86611	3217.51	1508.04	5.08E-05	0.000188	0.31989	33.067
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
27.87	0.93	167183.2	2440.191	68.80138	0.0002969	33549.8	22.3954	83196.27	38993.9	0.001313	0.004873	8.27144	855.02
27.34	1	167549.3	2348.264	68.95205	0.0002976	33623.3	22.4444	83378.47	39079.3	0.001316	0.004883	8.28956	856.89
27.87	0.94	167964.8	2440.191	69.12303	0.0002983	33706.7	22.5001	83585.21	39176.2	0.001319	0.004895	8.31011	859.02
28.21	0.93	171251.8	2500.092	70.47575	0.0003041	34366.3	22.9404	85220.95	39942.8	0.001345	0.004991	8.47274	875.83
28.21	0.93	171251.8	2500.092	70.47575	0.0003041	34366.3	22.9404	85220.95	39942.8	0.001345	0.004991	8.47274	875.83
27.76	1	171872.2	2420.967	70.73108	0.0003052	34490.8	23.0235	85529.71	40087.6	0.00135	0.005009	8.50344	879
28.21	0.94	172051.7	2500.092	70.80493	0.0003055	34526.8	23.0475	85619.01	40129.4	0.001351	0.005014	8.51232	879.92
27.87	1	173223.7	2440.191	71.28725	0.0003076	34762	23.2045	86202.24	40402.8	0.00136	0.005049	8.5703	885.91
28.21	1	177435.8	2500.092	73.02067	0.0003151	35607.3	23.7688	88298.33	41385.2	0.001393	0.005171	8.7787	907.46

Table 4-6: Input and output data's Cask

in:Radius	in:Lenght (Y)	in:Height (Z)	out:Thermal Load (kWh)	out:Area (m2)	Acidification	Carcinogenics	Ecotoxicity	Eutrophication	Fossil fuel depletion	Global warming	Non carcinogenics	Ozone depletion	Respiratory effects	Smog
5	10	1	8264.1484	100	3.40096929	1.47E-05	1658.4254	1.10704	4112.533	1927.53	6.49E-05	0.000241	0.4088716	42.2651
5	10	1.045	8329.7032	100	3.42794725	1.48E-05	1671.5807	1.11582	4145.156	1942.82	6.54E-05	0.000243	0.4121149	42.6004
5	10	1.061	8412.5221	100	3.46202995	1.49E-05	1688.2006	1.12692	4186.369	1962.14	6.61E-05	0.000245	0.4162124	43.024
5	10	1.033	8417.1299	100	3.46392623	1.49E-05	1689.1253	1.12753	4188.662	1963.22	6.61E-05	0.000245	0.4164404	43.0475
5	10	1.081	8504.6934	100	3.49996149	1.51E-05	1706.6972	1.13926	4232.237	1983.64	6.68E-05	0.000248	0.4207726	43.4954
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
20	62.497	1.061	191092.97	2499.88	78.6410517	0.000339361	38347.984	25.5982	95094.64	44570.6	0.001501	0.005569	9.4543901	977.302
19	62.497	1.2	191912.06	2374.89	78.9781362	0.000340816	38512.357	25.708	95502.25	44761.7	0.001507	0.005593	9.4949151	981.491
20	62.497	1.081	192984.8	2499.88	79.4196019	0.000342721	38727.631	25.8517	96036.08	45011.9	0.001515	0.005625	9.5479891	986.978
20	62.497	1.089	193339.38	2499.88	79.5655248	0.000343351	38798.787	25.8992	96212.53	45094.6	0.001518	0.005635	9.5655322	988.791
20	62.497	1.16	195020.92	2499.88	80.2575339	0.000346337	39136.234	26.1244	97049.32	45486.8	0.001531	0.005684	9.648727	997.391
20	62.497	1.197	198929.21	2499.88	81.8659245	0.000353278	39920.539	26.648	98994.23	46398.3	0.001562	0.005798	9.842091	1017.38
20	62.497	1.154	199803.82	2499.88	82.2258542	0.000354831	40096.052	26.7651	99429.46	46602.3	0.001569	0.005823	9.8853625	1021.85
20	62.497	1.2	203630.45	2499.88	83.800638	0.000361626	40863.969	27.2777	101333.7	47494.9	0.001599	0.005935	10.074686	1041.42

Table 4-7: input & output's Cube

Length (x)	Width (Y)	in:Height (Z)	out:Thermal Load (kWh)	out:Area (m2)	Acidification	Carcinogenics	Ecotoxicity	Eutrophication	Fossil fuel depletion	Global warming	Non carcinogenics	Ozone depletion	Respiratory effects	Smog
10.45	10	3.76	9010.651	104.5	3.708179568	1.60E-05	1808.231283	1.207039698	4484.019	2101.648627	7.08E-05	0.0002626	0.445805029	46.0829593
10.45	10	5.64	11218.36	104.5	4.616726637	1.99E-05	2251.268952	1.502778445	5582.656	2616.576954	8.81E-05	0.000327	0.555032439	57.3738196
14.36	10	3.76	11573.25	143.6	4.762775575	2.06E-05	2322.487255	1.550318447	5759.262	2699.351681	9.09E-05	0.0003373	0.572590745	59.1888254
16.64	10	3.76	13069.05	166.4	5.378346301	2.32E-05	2622.659947	1.750691242	6503.625	3048.232674	0.000102622	0.0003809	0.646595933	66.8387571
10.45	10	7.52	13456.05	104.5	5.537607026	2.39E-05	2700.320756	1.802531778	6696.206	3138.495316	0.00010566	0.0003922	0.665742587	68.8179508
10.45	16.99	3.76	13777.73	177.55	5.669990292	2.45E-05	2764.875225	1.845623504	6856.287	3213.524883	0.000108186	0.0004015	0.681657978	70.4631281
14.36	10	5.64	14177.87	143.6	5.834661149	2.52E-05	2845.174194	1.899225078	7055.411	3306.853772	0.000111328	0.0004132	0.701455049	72.5095555
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
49.4	44.69	18.8	197239.7	2207.7	81.17061731	0.000350277	39581.48378	26.42163239	98153.45	46004.27603	0.001548776	0.0057485	9.75849975	1008.73817
49.4	49.91	3.76	132655.1	2465.6	54.5919412	0.000235582	26620.84024	17.77007801	66013.88	30940.54	0.001041642	0.0038662	6.563156253	678.434838
40.84	49.91	18.8	186544.1	2038.3	76.76904559	0.000331283	37435.1315	24.98888845	92830.96	43509.64033	0.001464792	0.0054368	9.229333681	954.038157
49.4	44.69	16.92	187301.1	2207.7	77.08058343	0.000332627	37587.04768	25.09029631	93207.68	43686.20758	0.001470736	0.0054589	9.266787406	957.909757
42.09	49.91	18.8	190564.9	2100.7	78.42374065	0.000338423	38242.01567	25.52750385	94831.86	44447.45565	0.001496364	0.005554	9.428264549	974.601683
49.4	43.08	18.8	192040.9	2128.2	79.03117068	0.000341045	38538.21869	25.72522679	95566.38	44791.72282	0.001507954	0.005597	9.501291045	982.150447
49.4	49.91	15.04	193173.6	2465.6	79.49729178	0.000343056	38765.51479	25.87695263	96130.02	45055.90171	0.001516848	0.00563	9.557329089	987.943111
49.4	44.69	18.8	197239.7	2207.7	81.17061731	0.000350277	39581.48378	26.42163239	98153.45	46004.27603	0.001548776	0.0057485	9.75849975	1008.73817
49.4	49.91	16.92	203649	2465.6	83.80827057	0.000361659	40867.69095	27.28020791	101343	47499.19295	0.001599104	0.0059353	10.07560389	1041.51729
49.4	49.91	18.8	214112.3	2465.6	88.11424919	0.000380241	42967.42887	28.68183559	106549.9	49939.65029	0.001681264	0.0062403	10.59327756	1095.02932

Table 4-8: global warming potential (GWP) of 1 m2 aluminum in A&C&D stages

Parameter	Unit	A1-A3	A5	C1	C2	C3	C4	D
GWP-total	kg CO_2 eq	2.45E+01	3.77E-01	1.10E-03	8.96E-02	3.27E+00	1.23E-01	-5.35E+00
GWP-fossil	kg CO_2 eq	2.48E+01	8.97E-02	1.10E-03	8.90E-02	3.27E+00	1.22E-01	-5.35E+00
GWP-biogenic	kg CO_2 eq	-2.87E-01	2.87E-01	0	0	0	0	0
GWP-luluc	kg CO_2 eq	7.75E-03	1.17E-05	7.16E-08	6.01E-04	1.41E-05	2.26E-04	-1.16E-03
ODP	kg CFC11 eq	3.79E-07	3.83E-14	1.09E-14	8.76E-15	8.37E-13	2.87E-13	4.75E-11
AP	mol H^+ eq	1.36E-01	6.00E-05	1.62E-06	3.16E-04	1.21E-03	8.68E-04	-2.46E-02
EP-freshwater	kg P eq	2.26E-05	1.28E-08	4.95E-10	3.19E-07	1.78E-07	2.07E-07	-3.11E-06
EP-marine	kg N eq	1.70E-02	1.94E-05	4.43E-07	1.46E-04	5.31E-04	2.22E-04	-3.25E-03
EP-terrestrial	mol N eq	3.48E-01	2.84E-04	4.74E-06	1.63E-03	6.30E-03	2.44E-03	-3.53E-02
POCP	kg NMVOC eq	5.34E-02	5.11E-05	1.25E-06	2.85E-04	1.38E-03	6.74E-04	-9.96E-03
ADPE	kg Sb eq	1.25E-04	9.58E-10	1.31E-10	8.99E-09	1.71E-08	1.25E-08	2.27E-05
ADPF	MJ	3.59E+02	1.20E-01	2.34E-02	1.17E+00	1.44E+00	1.60E+00	-7.08E+01
WDP	m^3 world eq deprived	2.92E+00	4.02E-02	8.24E-05	9.95E-04	3.05E-01	1.34E-02	-7.39E-01

Table 4-9: Materials features of Aluminum cladding system prototype

Material	Thickness	Thermal conductivity	Density
Kalzip profile sheet (Aluminum alloy EN AW-3004,3005, 3105, 6025)	0.8 mm to 1.2 mm	120 w/m.k to 200 w/m.k	2700 kg/m³
XPS, polystyrene Insulation (/EN 12667/ and /EN 13164/ Annex C)	0.1 m to 0.2 m	0.034 W/(mK)	20 - 50 kg/m3
Vapor control layer	0.01 m	-	-
Trapezoidal deck	0.8 mm to 1.2 mm	120 w/m.k to 200 w/m.k	2700 kg/m³

Table 4-10: final analysis concerning energy consumption.

out:Heating (kWh)	out:Lighting (kWh)	out:Total (kWh)	out:Cooling (kWh/m2)	out:Heating (kWh/m2)	out:Lighting (kWh/m2)	out:Total (kWh/m2)	out:Thermal Load (kWh/m2)	out:Aluminum Ratio %	out:DA	out:cDA	out:UDI	out:UDI low	out:UDI up	out:sDA	out:GA
60917.61	18186.6	83982	6.427819	80.275622	23.965823	110.66926	86.703441	100	0	0	0	0	0	0	100
60915.81	18186.6	83979.47	6.426859	80.273244	23.965823	110.66593	86.700103	100	0	0	0	0	0	0	100
60914.19	18186.6	83977.23	6.426044	80.271117	23.965823	110.66298	86.697161	100	0	0	0	0	0	0	100
60911.5	18186.6	83973.14	6.424197	80.26757	23.965823	110.65759	86.691767	100	0	0	0	0	0	0	100
60910.95	18186.6	83972.04	6.423477	80.266842	23.965823	110.65614	86.690319	100	0	0	0	0	0	0	100
60905.49	18186.6	83956.29	6.409908	80.259646	23.965823	110.63538	86.669554	100	0	0	0	0	0	0	100
60904.65	18186.6	83955.03	6.409354	80.258546	23.965823	110.63372	86.667901	100	0	0	0	0	0	0	100
60901.7	18186.6	83954.14	6.412082	80.254649	23.965823	110.63255	86.666731	100	0	0	0	0	0	0	100
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
46915.67	18186.6	67431.17	3.068963	61.824232	23.965823	88.859018	64.893195	100	0	0	0	0	0	0	100
46914.33	18186.6	67429.27	3.068221	61.82247	23.965823	88.856514	64.890691	100	0	0	0	0	0	0	100
46913.05	18186.6	67427.44	3.067501	61.820782	23.965823	88.854107	64.888283	100	0	0.000091	0	100	0	0	100
46912.48	18186.6	67426.3	3.066734	61.820035	23.965823	88.852592	64.886769	100	0	0	0	0	0	0	100
46911.06	18186.6	67424.28	3.065959	61.818151	23.965823	88.849933	64.88411	100	0	0	0	0	0	0	100
46909.46	18186.6	67417.95	3.059732	61.816047	23.965823	88.841602	64.875779	100	0	0	0	0	0	0	100
46908.18	18186.6	67416.22	3.05913	61.81436	23.965823	88.839313	64.873489	100	0	0.000157	0	100	0	0	100
46906.91	18186.6	67413.88	3.057714	61.81269	23.965823	88.836227	64.870404	100	0	0	0	0	0	0	100
46905.42	18186.6	67411.79	3.056932	61.810728	23.965823	88.833483	64.86766	100	0	0.000041	0	100	0	0	100
46904.56	18186.6	67410.36	3.056175	61.809595	23.965823	88.831593	64.86577	100	0	0	0	0	0	0	100

Table 4-11: environmental effects caused by the annual energy consumption base on kwh in the B1 stage

in:trapezoidal sheeting aluminum	in:XPS Extruded Polystyrene	in:Corrugated sheet Aluminium	out:Cooling (kWh)	out:Heating (kWh)	out:Lighting (kWh)	out:Total (kWh)	out: DA	out: cDA	out: UDI	out: UDI low	out: UDI up	out: sDA	out: GA	Acidification	Carcinogenics	Ecotoxicity	Eutrophication	Fossil fuel depletion	Global warming	Non carcinogenics	Ozone depletion	Respiratory effects	Smog
0.0012	0.2	0.0012	2319.2	46905	18187	67410	0	0	0	0	0	0	100	27.7	0.0001	13527.7	9.03	33546	15723	0	0	3.34	345
0.0011	0.2	0.0012	2319.8	46905	18187	67412	0	0	0	100	0	0	100	27.7	0.0001	13528	9.03	33546	15723	0	0	3.34	345
0.001	0.2	0.0012	2320.4	46907	18187	67414	0	0	0	0	0	0	100	27.7	0.0001	13528.4	9.03	33548	15724	0	0	3.34	345
0.0009	0.2	0.0012	2321.4	46908	18187	67416	0	0	0	100	0	0	100	27.7	0.0001	13528.9	9.03	33549	15724	0	0	3.34	345
0.0008	0.2	0.0012	2321.9	46909	18187	67418	0	0	0	0	0	0	100	27.7	0.0001	13529.2	9.03	33550	15725	0	0	3.34	345
0.0012	0.2	0.0011	2326.6	46911	18187	67424	0	0	0	0	0	0	100	27.7	0.0001	13530.5	9.03	33553	15726	0	0	3.34	345
0.0011	0.2	0.0011	2327.2	46912	18187	67426	0	0	0	0	0	0	100	27.7	0.0001	13530.9	9.03	33554	15727	0	0	3.34	345
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
0.0011	0.1	0.001	4859.3	60899	18187	83945	0	0	0	0	0	0	100	34.5	0.0001	16845.7	11.2	41774	19579	0	0	4.15	429
0.0009	0.1	0.001	4860.6	60898	18187	83946	0	0	0	0	0	0	100	34.5	0.0001	16846	11.2	41774	19580	0	0	4.15	429
0.001	0.1	0.001	4859.9	60899	18187	83946	0	0	0	0	0	0	100	34.5	0.0001	16846	11.2	41774	19580	0	0	4.15	429
0.0008	0.1	0.001	4860.8	60900	18187	83947	0	0	0	0	0	0	100	34.5	0.0001	16846.3	11.2	41775	19580	0	0	4.15	429
0.001	0.1	0.0009	4864.8	60901	18187	83953	0	0	0	0	0	0	100	34.5	0.0001	16847.4	11.2	41778	19581	0	0	4.15	429
0.0009	0.1	0.0009	4865.5	60901	18187	83953	0	0	0	0	0	0	100	34.5	0.0001	16847.5	11.2	41778	19581	0	0	4.15	429
0.0008	0.1	0.0009	4865.8	60902	18187	83954	0	0	0	0	0	0	100	34.5	0.0001	16847.7	11.2	41779	19582	0	0	4.15	429
0.0012	0.1	0.0009	4863.8	60905	18187	83955	0	0	0	0	0	0	100	34.6	0.0001	16847.9	11.2	41779	19582	0	0	4.15	429
0.0011	0.1	0.0009	4864.2	60905	18187	83956	0	0	0	0	0	0	100	34.6	0.0001	16848.1	11.2	41780	19582	0	0	4.15	429
0.0012	0.1	0.0008	4874.5	60911	18187	83972	0	0	0	0	0	0	100	34.6	0.0001	16851.3	11.2	41787	19586	0	0	4.15	429
0.0011	0.1	0.0008	4875	60912	18187	83973	0	0	0	0	0	0	100	34.6	0.0001	16851.5	11.2	41788	19586	0	0	4.15	429
0.001	0.1	0.0008	4876.4	60914	18187	83977	0	0	0	0	0	0	100	34.6	0.0001	16852.3	11.2	41790	19587	0	0	4.15	429
0.0009	0.1	0.0008	4877.1	60916	18187	83979	0	0	0	0	0	0	100	34.6	0.0001	16852.8	11.2	41791	19587	0	0	4.15	429
0.0008	0.1	0.0008	4877.8	60918	18187	83982	0	0	0	0	0	0	100	34.6	0.0001	16853.3	11.2	41792	19588	0	0	4.16	430

Table 4-12: environmental impacts caused by the annual energy consumption per m2 in the B1 stage.

in:XPS Extruded Polystyrene	in:Corrugated sheet Aluminiuom	out:Cooling (kWh/m2)	out:Heating (kWh/m2)	out:Lighting (kWh/m2)	out:Total (kWh/m2)	out:Thermal Load (kWh/m2)	Acidification	Carcinogenics	Ecotoxicity	Eutrophication	Fossil fuel depletion	Global warming	Non carcinogenics	Ozone depletion	Respiratory effects	Smog
0.2	0.0012	3.056175	61.8096	23.96582	88.83159	64.86577	0.026694405	1.15195E-07	13.01707487	0.008689224	32.27950645	15.1293243	5.0934E-07	1.8905E-06	0.0032093	0.3317415
0.2	0.0012	3.056932	61.81073	23.96582	88.83348	64.86766	0.026695183	1.15198E-07	13.01745415	0.008689477	32.28044698	15.12976513	5.0936E-07	1.8906E-06	0.0032093	0.3317512
0.2	0.0012	3.057714	61.81269	23.96582	88.83623	64.870404	0.026696312	1.15203E-07	13.01800481	0.008689845	32.28181249	15.13040514	5.0938E-07	1.8906E-06	0.0032095	0.3317652
0.2	0.0012	3.05913	61.81436	23.96582	88.83931	64.873489	0.026697582	1.15209E-07	13.0186239	0.008690258	32.2833477	15.13112469	5.094E-07	1.8907E-06	0.0032096	0.331781
0.2	0.0012	3.059732	61.81605	23.96582	88.8416	64.875779	0.026698524	1.15213E-07	13.01908345	0.008690565	32.28448728	15.13165881	5.0942E-07	1.8908E-06	0.0032097	0.3317927
0.2	0.0011	3.065959	61.81815	23.96582	88.84993	64.88411	0.026701952	1.15228E-07	13.02075529	0.008691681	32.28863308	15.13360193	5.0949E-07	1.891E-06	0.0032102	0.3318353
0.2	0.0011	3.066734	61.82004	23.96582	88.85259	64.886769	0.026703047	1.15232E-07	13.02128889	0.008692037	32.2899563	15.13422212	5.0951E-07	1.8911E-06	0.0032103	0.3318489
0.2	0.0011	3.067501	61.82078	23.96582	88.85411	64.888283	0.02670367	1.15235E-07	13.02159272	0.00869224	32.29070972	15.13457525	5.0952E-07	1.8912E-06	0.0032104	0.3318567
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
0.1	0.001	6.403498	80.25056	23.96582	110.6199	86.65406	0.035661005	1.53889E-07	17.38948581	0.011607918	43.12213188	20.21123585	6.8043E-07	2.5255E-06	0.0042872	0.4431729
0.1	0.001	6.405109	80.2503	23.96582	110.6212	86.655412	0.035661562	1.53891E-07	17.38975713	0.011608099	43.12280469	20.21155119	6.8044E-07	2.5256E-06	0.0042873	0.4431798
0.1	0.001	6.404314	80.25123	23.96582	110.6214	86.655541	0.035661615	1.53892E-07	17.38978301	0.011608116	43.12286888	20.21158128	6.8044E-07	2.5256E-06	0.0042873	0.4431804
0.1	0.001	6.405445	80.25199	23.96582	110.6233	86.657437	0.035662395	1.53895E-07	17.3901635	0.01160837	43.1238124	20.2120235	6.8046E-07	2.5256E-06	0.0042874	0.4431901
0.1	0.0009	6.41068	80.25422	23.96582	110.6307	86.664895	0.035665464	1.53908E-07	17.39166015	0.011609369	43.12752376	20.21376301	6.8052E-07	2.5258E-06	0.0042878	0.4432283
0.1	0.0009	6.411588	80.25371	23.96582	110.6311	86.665295	0.035665629	1.53909E-07	17.39174042	0.011609423	43.12772282	20.21385631	6.8052E-07	2.5258E-06	0.0042878	0.4432303
0.1	0.0009	6.412082	80.25465	23.96582	110.6326	86.666731	0.03566622	1.53911E-07	17.39202859	0.011609615	43.12843742	20.21419124	6.8053E-07	2.5259E-06	0.0042879	0.4432377
0.1	0.0009	6.409354	80.25855	23.96582	110.6337	86.667901	0.035666701	1.53914E-07	17.39226338	0.011609772	43.12901965	20.21446413	6.8054E-07	2.5259E-06	0.0042879	0.4432437
0.1	0.0009	6.409908	80.25965	23.96582	110.6354	86.669554	0.035667382	1.53916E-07	17.3925951	0.011609993	43.12984225	20.21484968	6.8055E-07	2.526E-06	0.004288	0.4432521
0.1	0.0008	6.423477	80.26684	23.96582	110.6561	86.690319	0.035675927	1.53953E-07	17.39676216	0.011612775	43.14017565	20.21969292	6.8071E-07	2.5266E-06	0.004289	0.4433583
0.1	0.0008	6.424197	80.26757	23.96582	110.6576	86.691767	0.035676523	1.53956E-07	17.39705274	0.011612969	43.14089622	20.22003065	6.8073E-07	2.5266E-06	0.0042891	0.4433657
0.1	0.0008	6.426044	80.27112	23.96582	110.663	86.697161	0.035678743	1.53965E-07	17.39813519	0.011613692	43.14358047	20.22128875	6.8077E-07	2.5268E-06	0.0042894	0.4433933
0.1	0.0008	6.426859	80.27324	23.96582	110.6659	86.700103	0.035679953	1.53971E-07	17.39872559	0.011614086	43.14504451	20.22197494	6.8079E-07	2.5269E-06	0.0042895	0.4434083
0.1	0.0008	6.427819	80.27562	23.96582	110.6693	86.703441	0.035681327	1.53977E-07	17.39939545	0.011614533	43.14670562	20.2227535	6.8082E-07	2.527E-06	0.0042897	0.4434254

Table 4-13: environmental Impact caused by Aluminum cladding system

Parameter	Unit	A1-A3	A5	B1	C1	C2	C3	C4	D
GWP-total	kg CO_2 eq	3.72E+04	5.73E+02	1.15E+06	1.67E+00	1.36E+02	4.97E+03	1.87E+02	-8.13E+03
ODP	kg CFC11 eq	5.76E-04	5.82E-11	1.44E-01	1.66E-11	1.33E-11	1.27E-09	4.36E-10	7.22E-08
AP	mol H^+ eq	2.07E+02	9.12E-02	2.03E+03	2.46E-03	4.80E-01	1.84E+00	1.32E+00	-3.74E+01

Table 4-17: Physical feature of polycarbonate

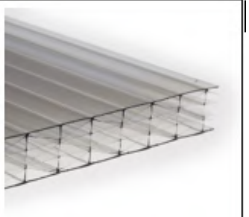
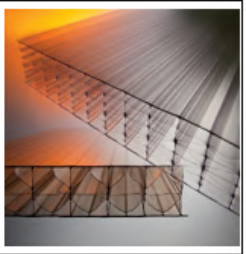
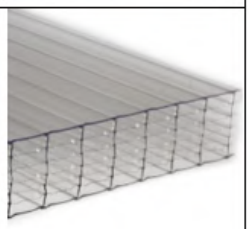
Thickness (mm)	Product	Light Transmission	U-Value (W/m2 K)	Nominal Sheet Weight (kg/m2)	Standard Sheet Sizes	Panels
25	Clear (PC25-C)	62%	1.4	3.1	Maximum Width: 2100mm Standard Max Length: 7m (and CTS)	
	Bronze (PC25-B)	11%				
	Opal (PC25-O)	28%				
	Bronze/Opal (PC25-B/O)	8%				
	Solar guard (PC25-SG)	7%	1.6	3.4		
32	Clear (PC32-C)	64%	1.25	3.6	Maximum Width: 2100mm Standard Max Length: 7m (and CTS)	
	Bronze (PC32-B)	7%				
	Opal (PC32-O)	33%				
	Bronze/Opal (PC32-B/O)	7%				
	Solar guard (PC32-SG)	4%	1.25	3.4		
35	Clear (PC35-C)	63%	1.2	3.9	Maximum Width: 2100mm Standard Max Length: 7m (and CTS)	
	Bronze (PC35-B)	7%				
	Opal (PC35-O)	33%				
	Bronze/Opal (PC35-B/O)	7%				
	Solar guard (PC35-SG)	4%	1.2	3.4		

Table 4-18: output analysis of polycarbonate

out:Transmittance	out:Conductivity	out:Thermal Load (kWh)	out:Cooling (kWh)	out:Heating (kWh)	out:Lighting (kWh)	out:Total (kWh)	out:Cooling (kWh/m2)	out:Heating (kWh/m2)	out:Lighting (kWh/m2)	out:Total (kWh/m2)	out:Thermal Load (kWh/m2)	out:DA	out:cDA	out:UDI	out:UDI low	out:UDI up	out:sDA
0.62	1.4	338173	83992.3	254181	6150.06	344324	110.6829	334.9532	8.10439	453.7405	445.6361	94.47	94.5301	3.16857	5.45005	91.3797	1
0.11	1.4	338105	66490.8	271614	6150.06	344255	87.61987	357.92633	8.10439	453.6506	445.5462	94.47	94.5302	3.16853	5.45005	91.3799	1
0.28	1.4	338182	73623.5	264559	6150.06	344332	97.01909	348.62867	8.10439	453.7521	445.6478	94.47	94.5303	3.16824	5.45	91.3801	1
0.08	1.4	338125	65200.9	272924	6150.06	344275	85.92005	359.65265	8.10439	453.6771	445.5727	94.47	94.5302	3.17011	5.45	91.3781	1
0.07	1.6	340143	64327.9	275815	6150.06	346293	84.76961	363.46186	8.10439	456.3359	448.2315	94.47	94.5302	3.16847	5.45003	91.3798	1
0.64	1.25	331974	86019.2	245955	6150.06	338124	113.3538	324.11256	8.10439	445.5707	437.4663	94.47	94.5302	3.17005	5.45	91.3784	1
0.07	1.25	332111	66801.7	265309	6150.06	338261	88.02954	349.61732	8.10439	445.7512	437.6469	94.47	94.5302	3.17031	5.45	91.378	1
0.33	1.25	332002	77270	254732	6150.06	338152	101.8243	335.67962	8.10439	445.6083	437.5039	94.4699	94.5302	3.16912	5.45003	91.3791	1
0.04	1.25	332995	66408.2	266587	6150.06	339145	87.51102	351.30097	8.10439	446.9164	438.812	94.47	94.5302	3.16928	5.45	91.379	1
0.63	1.2	329193	86561.7	242631	6150.06	335343	114.0687	319.73331	8.10439	441.9064	433.802	94.47	94.5302	3.17013	5.45003	91.3783	1
0.07	1.2	330195	68421.2	261774	6150.06	336346	90.1637	344.95919	8.10439	443.2273	435.1229	94.47	94.5302	3.16873	5.45003	91.3797	1
0.33	1.2	329251	78049.6	251202	6150.06	335401	102.8518	331.02671	8.10439	441.9829	433.8785	94.47	94.5302	3.17162	5.45	91.3768	1
0.04	1.2	330295	67210.5	263085	6150.06	336445	88.56818	346.6859	8.10439	443.3585	435.2541	94.47	94.5302	3.16793	5.45	91.3802	1

Table 4-19: Environmental Impact of Producing and Transmitting 1 kWh of Low-Voltage Electricity in Boston

Impact category	Reference unit	Result
Acidification	kg SO_2 eq	0.000411533
Carcinogenics	CTUh	1.7759E-09
Ecotoxicity	CTUe	0.200677104
Eutrophication	kg N eq	0.000133957
Fossil fuel depletion	MJ surplus	0.497635447
Global warming	kg CO_2 eq	0.233240495
Non carcinogenics	CTUh	7.85226E-09
Ozone depletion	kg CFC-11 eq	2.91448E-08
Respiratory effects	kg $PM_{2.5}$ eq	4.94753E-05
Smog	kg O_3 eq	0.005114277

Table 4-20: The annual environmental Impacts

Thickness,Transmittance, U-value	Acidification	Carcinogenic	Ecotoxicity	Eutrophication	Fossil fuel depletion	Global warming	Non carcinogenic	Ozone depletion	Respiratory effects	Smog
0.025, 0.62, 1.4	141.7005	0.000611	69097.8502	46.124548	171347.6	80310.19	0.002704	0.010035	17.03551	1760.966
0.025, 0.11, 1.4	141.6724	0.000611	69084.1616	46.115411	171313.7	80294.28	0.002703	0.010033	17.03214	1760.617
0.025, 0.28, 1.4	141.7041	0.000612	69099.6283	46.125735	171352	80312.26	0.002704	0.010035	17.03595	1761.011
0.025, 0.08, 1.4	141.6807	0.000611	69088.1982	46.118105	171323.7	80298.97	0.002703	0.010034	17.03313	1760.72
0.025, 0.67, 1.6	142.511	0.000615	69493.088	46.388379	172327.7	80769.56	0.002719	0.010093	17.13295	1771.039
0.032, 0.64, 1.25	139.1491	0.0006	67853.7202	45.29406	168262.4	78864.18	0.002655	0.009855	16.72878	1729.259
0.032, 0.07, 1.25	139.2055	0.000601	67881.2102	45.31241	168330.6	78896.13	0.002656	0.009859	16.73556	1729.96
0.032, 0.33, 1.25	139.1609	0.000601	67859.4457	45.297882	168276.6	78870.83	0.002655	0.009855	16.73019	1729.405
0.032, 0.04, 1.25	139.5694	0.000602	68058.6429	45.430851	168770.6	79102.36	0.002663	0.009884	16.7793	1734.482
0.035, 0.63, 1.2	138.0048	0.000596	67295.6942	44.921564	166878.6	78215.6	0.002633	0.009774	16.5912	1715.038
0.035, 0.07, 1.2	138.4173	0.000597	67496.8484	45.055839	167377.5	78449.4	0.002641	0.009803	16.6408	1720.164
0.035, 0.33, 1.2	138.0287	0.000596	67307.3418	44.929339	166907.5	78229.14	0.002634	0.009775	16.59408	1715.335
0.035, 0.04, 1.2	138.4583	0.000597	67516.8263	45.069175	167427	78472.62	0.002642	0.009806	16.64572	1720.673

Table 4-21: The Area of each geographic direction

Geographic direction	**North (m^2)**	**East (m^2)**	**Sout (m^2)**	**West (m^2)**
Area	492.067396	267.728699	492.067396	267.728699
All surface Area	1519.59219 (m^2)			
Base area	758.855686			

Table 4-22: Max and Min Area of each cell

	North	East	Sout	West
Min Area **(m^2)**	4.441	5.354	4.441	5.354
Max Area **(m^2)**	11.268	11.268	11.268	11.268

Table 4-23: Max and Min Area of each cell

	North	East	Sout	West
Min Area **(m^2)**	4.441	5.354	4.441	5.354
Max Area **(m^2)**	11.268	11.268	11.268	11.268

Table 4-24: Aluminum Cladding system features

Material	Thickness	Thermal conductivity	Density
Kalzip profile sheet (Aluminum alloy EN AW-3004,3005, 3105, 6025)	1.2 mm	200 w/m.k	2700 kg/m³
XPS, polystyrene Insulation (/EN 12667/ and /EN 13164/ Annex C)	0.2 m	0.034 W/(mK)	20 - 50 kg/m3
Vapor control layer		-	-
Trapezoidal deck	1.2 mm	200 w/m.k	2700 kg/m³

Table 4-25: Polycarbonate cladding system

Thickness (mm)	Product	Light Transmission	U-Value (W/m2 K)	Nominal Sheet Weight (kg/m2)	Standard Sheet Sizes
25	Clear (PC25-C)	62%	1.4	3.1	Maximum Width: 2100mm Standard Max Length: 7m (and CTS)
	Bronze (PC25-B)	11%			
	Opal (PC25-O)	28%			
	Bronze/Opal (PC25-B/O)	8%			
	Solar guard (PC25-SG)	7%	1.6	3.4	
32	Clear (PC32-C)	64%	1.25	3.6	Maximum Width: 2100mm Standard Max Length: 7m (and CTS)
	Bronze (PC32-B)	7%			
	Opal (PC32-O)	33%			
	Bronze/Opal (PC32-B/O)	7%			
	Solar guard (PC32-SG)	4%	1.25	3.4	
35	Clear (PC35-C)	63%	1.2	3.9	Maximum Width: 2100mm Standard Max Length: 7m (and CTS)
	Bronze (PC35-B)	7%			
	Opal (PC35-O)	33%			
	Bronze/Opal (PC35-B/O)	7%			
	Solar guard (PC35-SG)	4%	1.2	3.4	

Table 4-26: initial data outputs

	A	B	C	D	E	F	G	H	I	J	K	L
1	TP	MinN	MaxN	MinE	MaxE	MinS	MaxS	MinW	MaxW	TL (kwh/m2	sDA	ASE
2	3	0.05	0.6	0.25	0.7	0.15	0.55	0.35	0.4	145.4575	1E-05	23.9
3	8	0	0.5	0.1	0.9	0.25	0.7	0.1	0.7	158.8421	1E-05	26.62
4	8	0.25	0.85	0.05	0.5	0.15	0.8	0.05	0.8	176.3492	1E-05	12.5
5	4	0.3	0.85	0.2	0.8	0.25	0.35	0.35	0.8	194.7318	1E-05	22.87
6	10	0	0.65	0.2	0.5	0.35	0.75	0.15	0.6	154.5151	1E-05	26.96
7	8	0.25	0.6	0.1	0.6	0.2	0.45	0.1	0.75	137.075	1E-05	0.658
8	5	0.05	0.85	0.05	0.9	0.15	0.7	0	0.4	172.5938	73.65	54.75
9	3	0.05	0.5	0.2	0.5	0.35	0.85	0.3	0.45	163.2011	1.689	28.95
10	1	0.05	0.6	0.35	0.6	0.25	0.85	0.05	0.6	163.7505	7.095	35.19
11	4	0	0.6	0.15	0.6	0.15	0.35	0.2	0.8	125.9108	1E-05	3.948
12	10	0.25	0.4	0	0.9	0.1	0.85	0.15	0.5	157.3942	1E-05	38.68
13	1	0.05	0.55	0.15	0.6	0.2	0.5	0	0.45	119.5755	1E-05	18.03
14	3	0.15	0.75	0.05	0.5	0.3	0.9	0.1	0.9	188.3917	2.365	29.34
15	8	0.3	0.75	0.35	0.7	0.25	0.45	0	0.35	158.5455	1E-05	2.633
16	2	0.05	0.5	0.05	0.4	0.3	0.6	0.3	0.9	143.1936	24.29	28.61
17	1	0.3	0.75	0.3	0.4	0.1	0.45	0.25	0.45	147.9244	1E-05	10.74
18	1	0.25	0.7	0.1	0.4	0.2	0.5	0.1	0.7	140.9705	1E-05	14.19
19	7	0.05	0.65	0.25	0.5	0.1	0.65	0.05	0.9	140.3188	28.17	29.8
20	10	0	0.55	0.3	0.8	0.1	0.8	0.3	0.6	160.1002	1E-05	34.66
21	3	0.25	0.8	0.15	0.8	0.3	0.65	0.05	0.55	185.4915	1E-05	43.8
22	5	0.3	0.35	0.25	0.9	0.3	0.5	0.3	0.7	166.5679	94.62	50.98
23	5	0.15	0.65	0.1	0.6	0.3	0.55	0.1	0.75	145.6552	73.33	44.19
24	10	0.1	0.9	0.1	0.6	0.05	0.4	0.35	0.6	151.0769	1E-05	7.005
25	10	0.1	0.6	0.3	0.5	0.1	0.35	0.05	0.5	110.7966	1E-05	1.315
26	11	0.05	0.4	0.15	0.7	0.3	0.7	0.15	0.6	139.2096	45.39	43.74
27	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
7476	5	0.3	0.4	0.35	0.4	0.35	0.35	0.35	0.4	98.16269	45.71	3.325
7477	5	0.3	0.35	0.3	0.4	0.2	0.35	0.35	0.6	119.0443	79.3	8.98
7478	5	0.35	0.35	0.25	0.4	0.25	0.35	0.3	0.7	102.8612	67.07	14.05
7479	5	0.35	0.35	0.35	0.4	0.25	0.35	0.35	0.35	73.32732	24.66	8.785
7480	5	0.3	0.35	0.35	0.4	0.25	0.35	0.3	0.5	105.9406	67.64	9.123
7481	5	0.35	0.35	0.35	0.4	0.1	0.35	0.3	0.6	95.83827	51.42	7.253
7482	5	0.35	0.35	0.2	0.4	0.1	0.35	0.3	0.6	92.5549	45.82	5.28
7483	5	0.35	0.35	0.35	0.4	0.25	0.35	0.3	0.6	88.9295	48.67	9.443
7484	5	0.35	0.35	0.35	0.4	0.1	0.35	0.35	0.45	81.39056	26.74	2.648
7485	5	0.35	0.35	0.3	0.4	0.35	0.35	0.35	0.45	87.6371	46.05	7.235
7486	9	0.35	0.4	0.3	0.4	0.35	0.35	0.35	0.4	109.6708	63.16	5.638
7487	5	0.3	0.4	0.35	0.4	0.05	0.35	0.35	0.45	103.1132	49.36	3.663
7488	5	0.35	0.35	0.35	0.5	0.25	0.35	0.3	0.65	105.8484	73.01	19.31
7489	5	0.35	0.35	0.35	0.4	0.25	0.35	0.3	0.6	101.9822	72.69	15.36
7490	5	0.35	0.35	0.3	0.4	0.25	0.35	0.35	0.4	97.67419	68.39	16.02
7491	5	0.35	0.35	0.35	0.4	0.15	0.35	0.05	0.4	71.72892	7.095	1.353
7492	5	0.35	0.35	0.35	0.4	0.35	0.35	0.3	0.45	74.54052	19.74	0
7493	5	0.35	0.35	0.25	0.4	0.35	0.35	0.3	0.7	91.36198	44.74	5.263
7494	9	0.3	0.35	0.35	0.4	0.35	0.35	0.35	0.4	94.75561	38.99	1.653
7495	5	0.3	0.35	0.3	0.5	0.2	0.35	0.3	0.5	118.1764	83.59	12.27
7496	5	0.3	0.4	0.3	0.4	0.25	0.35	0.3	0.6	121.5152	87.12	13.43
7497	5	0.35	0.35	0.35	0.4	0.2	0.35	0.3	0.6	100.087	64.58	9.955
7498	5	0.35	0.35	0.35	0.4	0.35	0.35	0.35	0.45	88.81967	46.71	7.893
7499	5	0.3	0.35	0.35	0.4	0.25	0.35	0.3	0.6	121.6984	91.95	15.7
7500	5	0.35	0.35	0.35	0.4	0.1	0.35	0.35	0.45	81.39314	27.74	2.648
7501	5	0.3	0.4	0.3	0.4	0.2	0.35	0.35	0.4	118.6957	85.97	11.97
7502	5	0.35	0.35	0.3	0.4	0.2	0.35	0.25	0.65	96.03375	57.68	6.01

Table 4-27: optimized model based on wallacei analysis

TP	MinN	MaxN	MinE	MaxE	MinS	MaxS	MinW	MaxW	TL (kwh/m2)	sDA	ASE
5	0.25	0.45	0.3	0.4	0.2	0.35	0.3	0.7	125.1971	88.245676	10.63
5	0.3	0.35	0.1	0.5	0.25	0.35	0.35	0.45	118.935536	90.309762	20.963
5	0.3	0.35	0.2	0.4	0.2	0.35	0.3	0.45	112.627717	74.024724	7.6625
9	0.35	0.35	0.3	0.4	0.2	0.4	0.35	0.4	97.387288	66.392245	14.705
5	0.25	0.4	0.35	0.35	0.2	0.35	0.3	0.55	105.67458	60.507049	3.715
5	0.3	0.4	0.3	0.4	0.25	0.35	0.3	0.5	120.817915	93.049223	15.4
5	0.3	0.35	0.3	0.35	0.25	0.35	0.3	0.6	118.48388	86.400553	12.413
5	0.35	0.35	0.2	0.35	0.25	0.35	0.3	0.45	92.715945	50.978793	10.1
5	0.35	0.35	0.35	0.4	0.2	0.35	0.25	0.65	99.36136	65.612493	9.2975
5	0.35	0.35	0.35	0.4	0.25	0.35	0.35	0.5	101.501202	73.024682	16.678
5	0.35	0.35	0.35	0.35	0.05	0.35	0.05	0.4	69.51709	1.013514	0.3375
5	0.35	0.35	0.35	0.35	0.2	0.35	0.3	0.7	90.232067	43.936731	4.6925
5	0.35	0.4	0.35	0.4	0.25	0.35	0.35	0.45	125.957061	96.711799	18.368
5	0.35	0.35	0.3	0.4	0.2	0.35	0.3	0.4	93.672669	51.421813	8.64
5	0.35	0.4	0.3	0.45	0.3	0.35	0.35	0.65	135.092894	99.344327	29.073
5	0.35	0.35	0.35	0.35	0.1	0.35	0.35	0.4	80.205076	25.106703	2.6475
5	0.3	0.4	0.35	0.35	0.2	0.35	0.3	0.6	109.868765	68.259386	5.3875
5	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	64.039581	0.00001	0
5	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.4	75.475133	21.710341	1.9725
5	0.3	0.35	0.25	0.4	0.25	0.35	0.3	0.5	116.693595	84.047739	13.07
5	0.35	0.35	0.35	0.35	0.05	0.35	0.35	0.45	80.412565	26.049129	2.31
5	0.35	0.35	0.3	0.35	0.2	0.35	0.25	0.65	96.033746	57.680106	6.01
5	0.35	0.35	0.3	0.35	0.35	0.35	0.35	0.45	85.673049	40.789688	4.605
5	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	64.039581	0.00001	0
5	0.35	0.35	0.35	0.35	0.1	0.35	0.35	0.35	68.144747	4.054049	0.675
5	0.35	0.4	0.3	0.45	0.25	0.35	0.3	0.75	133.688594	99.000099	20.343
5	0.35	0.35	0.35	0.35	0.25	0.35	0.3	0.6	88.929498	48.666537	9.4425
5	0.35	0.35	0.35	0.35	0.15	0.35	0.05	0.4	71.728923	7.094614	1.3525
5	0.35	0.35	0.3	0.35	0.2	0.35	0.25	0.65	96.033746	57.680106	6.01

Table 4-28: tow optimized model

Data group	Model Type	Thermal Load	sDA	ASE
Wallacei data	5	93.672669	51.421813	8.64
All data	9	93.236228	53.378883	7.325

Table 4-29: the optimized model features

Model type	Light Transmission	U-value (w/m2k)	Thickness (mm)
5	64%	1.25	32
9	63%	1.2	35

Table 4-30: Optimized model result

Model type	Min N	Max N	Min E	Max E	Min S	Max S	Min W	Max W	TL (kwh/m2)	sDA	ASE
5	0.35	0.35	0.3	0.4	0.2	0.35	0.3	0.4	93.672669	51.421813	8.64
9	0.35	0.35	0.3	0.35	0.2	0.35	0.3	0.4	93.236228	53.378883	7.325

Table 4-31: Environmental Impact Analysis

MT[1]	TL	AC	CA	ECO	EUT	FFD	GW	NCA	OD	RE	S
5	93.67267	0.038549389	1.6635E-07	18.79796	0.01254811	46.61484053	21.84826	7.355E-07	2.73007E-06	0.004634	0.479068
9	93.23623	0.038369779	1.6558E-07	18.71038	0.01248965	46.39765202	21.74646	7.321E-07	2.71735E-06	0.004613	0.476836

[1] Tl (Thermal Load , kwh/m2), AC (Acidification, kg SO_2 eq), CA (Carcinogenic, CTUh), ECO (Ecotoxicity, CTUe), EUT (Eutrophication, kg N eq), FFD (Fossil fuel depletion, MJ surplus), GW (Global warming, kg CO_2 eq), NCA (Non carcinogenic, CTUh), OD (Ozone depletion, kg CFC-11 eq), RE (Respiratory effect, kg $PM_{2.5}$ eq), S (Smog, kg O_3 eq)

Chapter 5

Table 5-1: Output data for each Geometry with 100-meter square area

Model	TL	AC	CA	ECO	EUT	FFD	GW	NCA	OD	RE	S
Sphere	6234.63856	2.565759	1.1072 1E-05	1251.149	0.835173453	3102.577	1454.17	4.9E -05	0.000182	0.308461	31.88566565
Cube	9010.65068	3.70818	1.60E-05	1808.231	1.207039698	4484.019	2101.649	7.08 E-05	0.000263	0.445805	46.08295929
Cask	8264.14839	3.400969	1.47E-05	1658.425	1.107040493	4112.533	1927.534	6.49 E-05	0.000241	0.408872	42.26514014

Table 5-2: optimized model of polycarbonate and aluminum cladding systems

	out: Cooling (kWh)	out: Heating (kWh)	out: Lighting (kWh)	out: Total (kWh)
Aluminum	2319.195606	46904.56263	18186.60133	67410.35956
polycarbonate	86561.65844	242631.4407	6150.060827	335343.16

Table 5-3: Environmental Impact of different cladding systems

	AC	CA	ECO	EUT	FFD	GW	NC	OD	RE	S
Aluminum	27.7415875	1.20E-04	13527.72	9.030089536	33545.78	15722.83	5.29E-04	1.96E-03	3.34E+00	344.7553
Polycarbonate	138.0047767	5.96E-04	67295.69	4.49E+01	166878.6	78215.6	2.63E-03	9.77E-03	1.66E+01	1.72E+03

Table 5-4: Optimized models features.

TP	AL Ratio	PL Ratio	Cooling	Heating	Lighting	TL	sDA	ASE
5	93.18	6.83	13704.53	57379.51	8006.35	71084.04	51.42181	8.64
9	93.193	6.82	13689.41	57063.43	8017.657	70752.84	53.37888	7.325

Table 5-5: light openings Area in model 5.in each cell

Geographical direction (TP_5)	North	East	Sout	West
Min Area **(m^2)**	0	0.84	0.2	0.49
Max Area **(m^2)**	0	1.65	1.23	1,71

Table 5-6: light openings Area in model 9 in each cell

Geographical direction (TP9)	North	East	Sout	West
Min Area **(m²)**	0	0.65	0.20	0.66
Max Area **(m²)**	0	1.28	1.24	1.71

Table 5-7: Comparison 4 cladding

Cladding systems	Cooling (kWh)	Heating (kWh)	Lighting (kWh)	Total (kWh)	sDA %	ASE %
Aluminum	2319.196	46904.57	18186.60	67410.36	0	0
polycarbonate	86561.658	242631.44	6150.06	335343.16	74.30	55.40
Hybrid Model 5	13704.528	57379.51	8006.35	79090.39	51.70	8.60
Hybrid model 9	13689.410	57063.43	8017.66	78770.50	54.70	7.3

Table 5-8: Comparison Environmental Impacts of different

	AC	CA	ECO	EUT	FFD	GW	NCA	OD	RE	S
Aluminum	27.7415875	0.0001 19714	13527. 71574	9.0300 8954	33545 .784	15722. 8256	0.0005 29324	0.001 9647	3.3351 47762	344.75 5251
polycarbonate	138.00 47767	0.0005 95536	67295. 6942	44.921 5637	16687 8.64	78215. 6046	0.0026 33202	0.009 7735	16.591 20344	1715.0 3781
Model 5	32.548 30547	0.0001 40457	15871. 63042	10.594 7114	39358 .182	18447. 0817	0.0006 21038	0.002 3051	3.9130 20772	404.49 0162
model 9	32.416 65935	0.0001 39889	15807. 43542	10.551 8596	39198 .992	18372. 4699	0.0006 18526	0.002 2958	3.8971 9402	402.85 4146

Table 5-9: area of opening in each direction

	North (m²)	East (m²)	Sout (m²)	West (m²)
Model 5	0	36.37	37.98	29.33
Model 9	0	29.88	37.98	35.71

Table 5-10: Aluminum Ration and Polycarbonate Ratio in each geographic direction

Model Type	AL Ratio	PL Ratio
Model 5	93.17702	6.822985
Model 9	93.18423	6.815767

Table 5-11: Area percentage of skylights by geographical direction

Model Type	North(m2)	East(m²)	Sout (m²)	West (m²)
Moddel5	0	13.58458	7.718461	10.95507
Model 9	0	11.1605	7.718461	13.33806