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Integrating BIM Processes with LEED Certification: A Comprehensive Framework for Sustainable Building Design

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Abstract: In response to the pressing demand for sustainable building practices within the Architecture, Engineering, and Construction (AEC) sector, this study investigates the integration of building information modeling (BIM) processes with the Leadership in Energy and Environmental Design (LEED) certification system, with a primary focus on enhancing sustainable design strategies. The objectives are twofold: firstly, to comprehensively understand the existing synergies between BIM and LEED, and secondly, to develop innovative methods that facilitate a seamless integration of these two crucial components. The study is structured into four distinct phases, each contributing to a comprehensive understanding of the synergistic relationship between BIM and LEED. In Phase 1, the "LEED-BIM Worksheets" is introduced, versatile tools designed to facilitate sustainable strategy formulation. These worksheets transparently identify roles, assess competencies, estimate certification levels, and enhance communication among stakeholders. Phase 2 highlights the "BIM Uses for Project Phase" diagram, emphasizing interdependencies between BIM uses and processes. This diagram provides insights into collaborative synergies among BIM uses and streamlines process mapping. Phase 3 introduces the "Liv1 Process Map", a transformative visual representation of the building process. Integrated within building execution plans (BEPs), this map intricately weaves together responsible parties and BIM uses, fostering cohesive collaboration. Phase 4 extends the research with the introduction of the "Liv.2 Process Map". This extension integrates selected BIM uses from the LEED Pilot Credits Library, emphasizing alignment between BIM processes and LEED credit criteria. Collectively, this research illuminates the potential for streamlining sustainable practices within the AEC sector. The findings offer valuable insights for both practitioners and researchers, empowering them to navigate the integration of BIM technology with LEED certification. By harmonizing digital transformation with ecological consciousness, this research significantly contributes to advancing sustainable building practices.

Keywords: building information modeling (BIM); Leadership in Energy and Environmental Design (LEED) certification; sustainable building practices; BIM integration; process optimization; sustainability assessment framework; green building certification; collaborative planning; green building strategies; environmental impact assessment

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1. Introduction

1.1. Background and Context

The Architecture, Engineering, and Construction (AEC) sector faces significant challenges, including climate change and rising energy costs [1,2]. This sector, comprising diverse professionals responsible for various stages of building and infrastructure projects, is under increasing pressure to adopt sustainable building practices [3]. As the urgency for sustainability grows, there is a greater focus on innovative solutions to reduce environmental impact and enhance energy efficiency [4,5]. Over the past three decades, national and international green building certification bodies have emerged, providing valuable frameworks to promote sustainability in construction projects [6].

One prominent certification system in this domain is the Leadership in Energy and Environmental Design (LEED) green building rating system, initiated by the U.S. Green Building Council in 1998 [7]. However, it is worth noting that while LEED holds global recognition, various regions may also have their own localized green building standards and rating systems. Central to green building certification programs is the accumulation of points across different categories to achieve the final certification level. The LEED system offers multiple avenues to earn points, including pilot credits, regional priority, and exemplary performance [8]. Nevertheless, meeting the specific and stringent sustainability criteria within the LEED framework often requires advanced digital analysis and modeling tools [9].

In response to these sustainability demands, the concept of green building information modeling (BIM) has gained prominence [10]. Green BIM involves strategically using BIM technology to achieve sustainability objectives. It empowers architects and engineers to assess a building's environmental impact and energy performance during the initial design phases [11], allowing for the early identification and resolution of sustainability challenges [12,13]. Zhang et al. [14] provide an overview of the current state of research in mathematical models for building physics and energy technologies, focusing on environmentally friendly integrated energy management systems.

Efficient data management and coordination among digital models are crucial for enabling seamless collaboration among design stakeholders, leading to informed decision-making on sustainability and improved project outcomes [15]. Additionally, BIM supports quantity estimation, document review, and generation, contributing to the attainment of LEED credits required for higher environmental certification levels [16].

However, integrating BIM with environmental assessment systems presents challenges, including the extended time needed for energy evaluations, the requirement for precise and relevant information, and potential unfamiliarity with assessment methodologies among project teams [17]. Incorporating sustainability into the construction process introduces complexities into traditional workflows, demanding meticulous management of interconnected activities and effective communication among diverse stakeholders [18]. Rajabi et al. [19] emphasize the importance of developing strategies to facilitate BIM implementation, offering practical and managerial insights for organizations and policymakers to enhance BIM capabilities.

BIM technology facilitates accurate simulations, performance analyses, and interdisciplinary integration among various construction project disciplines [20]. This is achieved by providing continuous access to real-time information, enabling seamless coordination of people, resources, and information, which is essential for successful design outcomes [21]. To address these complexities, the BIM execution plan (BEP) emerges as a valuable solution, complementing the design process [22]. The BEP equips all stakeholders with critical information, including project objectives, deadlines, design phases, roles and responsibilities, BIM uses, level of development (LOD), and delivery strategy. Within the BEP, the BIM process map offers a comprehensive overview of the entire construction process, specifying responsible entities for each activity and outlining information exchange protocols at various stages. Additionally, it defines the required LOD for BIM deliverables [23,24]. Crucially, the BEP outlines sustainability objectives, facilitating the early assessment of whether the design team possesses the necessary resources and competencies to address both sustainability and BIM integration challenges [24].

1.2. Literature Review

The convergence of digital transformation through building information modeling (BIM) processes and ecological transformation via green building certifications is a critical area of investigation within the Architecture, Engineering, and Construction (AEC) sector [25]. Numerous studies have explored the alignment of sustainability goals with BIM practices in AEC, aiming to optimize sustainable design and attain green building certifications.

For example, Gandhi and Jupp conducted a study in Australia focusing on a commercial office building, examining the integration of environmental certification processes, particularly the Green Star system, with BIM modeling [26]. Their research, based on interviews, identified gaps and challenges in the design process and explored ways to maximize BIM's utility in certifying sustainable buildings. Similarly, Zanni et al. developed a sustainable BIM design process, emphasizing critical decision points in the design process, such as information requirements and levels of detail for informed decision-making [27]. Their study involved interactions with sustainable design experts and the use of questionnaires to gather insights into the design stages of the RIBA Plan of Work 2013.

Salgueiro and Ferries contributed to the field by integrating environmental design criteria into the schematic phase of construction using BIM technology [28]. Their work involved creating a process map that outlined the necessary information exchange for seamless integration of sustainability aspects into the BIM workflow. Notably, this study highlighted interoperability challenges between BIM software and analysis tools, emphasizing the significance of analysis outcomes.

Additionally, Rodriguez-Trejo et al. presented a structured methodology aimed at automating the extraction of design criterion indicators through BIM to facilitate sustainability decision-making [29]. Their research adapted the analytic hierarchy process (AHP) to the context of Qatar. Lastly, Marzouk et al. explored the integration of environmental assessment methodology (EAM) workflows into the design phase using BIM methodology [30]. Their work proposed a structured methodology for categorizing and balancing subjective priorities from top-level management for buildings and facilities. This aimed to establish an approach for defining information and operational requisites in early project phases, prioritizing and assigning value to these prerequisites. The authors adapted the analytic hierarchy process (AHP) to the specific context of Qatar.

Despite the increasing emphasis on sustainability in the AEC sector and the presence of national and international green building certification bodies, a notable research gap exists concerning the integration of BIM processes with the Leadership in Energy and Environmental Design (LEED) certification system. While several studies have explored broader sustainability and BIM integration in construction, few have delved into the specific customization of BIM processes to align with the stringent requirements of LEED certification. This research gap underscores the necessity for a comprehensive exploration addressing the opportunities and challenges of utilizing BIM technology to achieve higher tiers of LEED certification while streamlining the sustainability assessment process.

1.3. Research Objectives and Contributions

To enhance our understanding of the synergy between BIM processes and LEED certification, we build upon the integrated green BIM process model proposed by Wu and Issa [31]. While acknowledging their valuable insights into BIM's potential and limitations in green building projects, our study seeks to address these limitations and further validate the proposed model.

Our study advocates for the implementation of the BIM execution plan (BEP) as a solution to the challenges stemming from the integration of BIM and sustainability. We present a comprehensive framework that delineates roles, responsibilities, and information exchange protocols throughout the construction process. This structured approach represents a novel contribution, offering clarity in navigating the complexities of BIM and sustainability integration. We emphasize the BEP's role in managing project quality and ensuring sustainability in the AEC sector, highlighting the importance of structured information, protocols, and responsibilities to achieve sustainability goals within BIM environments (Figure 1).

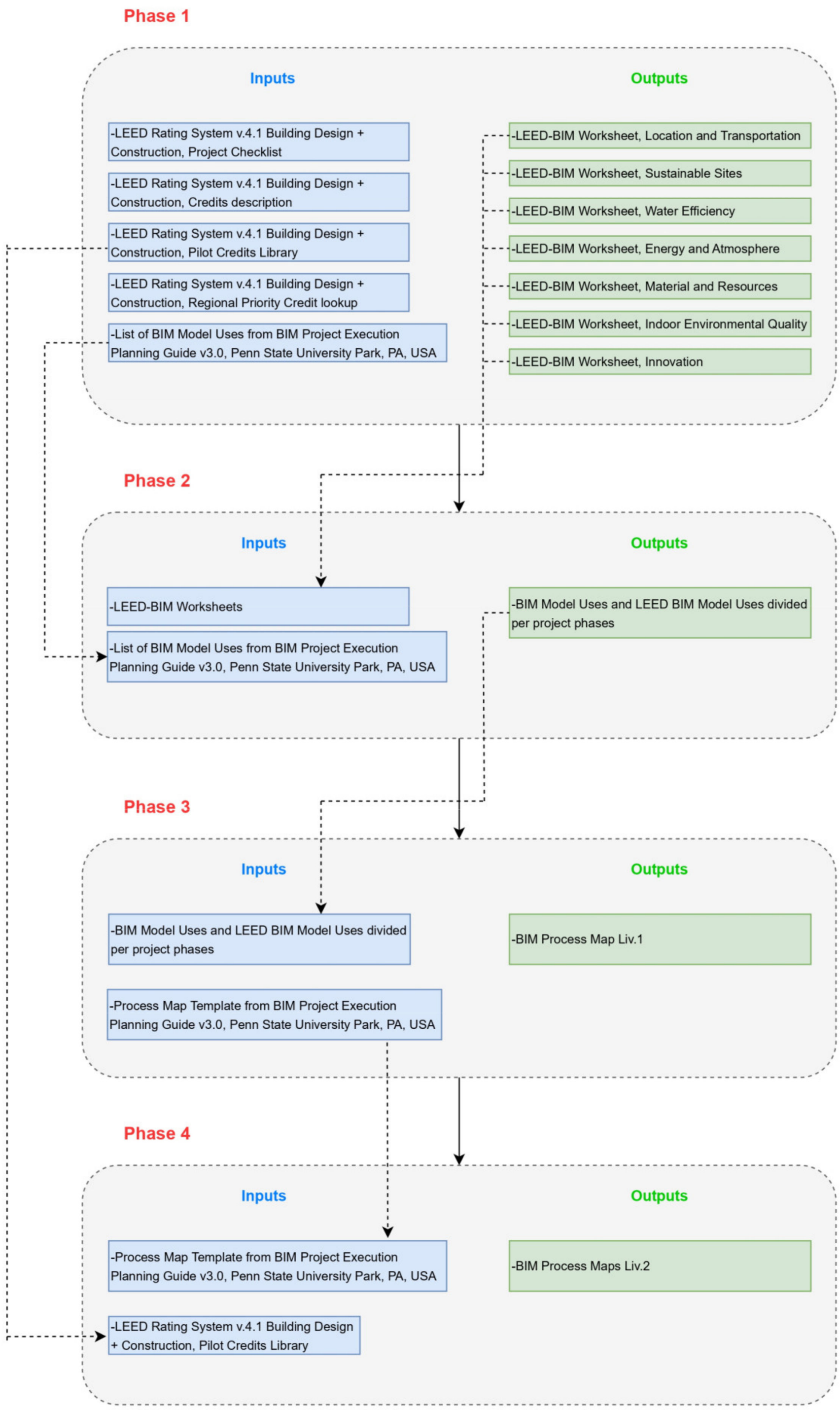


Figure 1. Diagram illustrating the sequential research phases along with their respective inputs and outputs.

A key focus of this research is the proactive integration of sustainability goals with BIM technology and the LEED rating system during the early design stages. This approach sets our work apart by enabling architects and engineers to address sustainability concerns upfront, reducing the need for corrective actions later in the project lifecycle.

Furthermore, we delve into the intricacies of acquiring pilot credits within the LEED Innovation category. We provide insights into effectively pursuing these credits, thereby enhancing a building's overall sustainability profile and increasing the prospects of achieving higher levels of LEED certification, including bonus points from the regional priority and exemplary performance categories.

In summary, our research aims to contribute valuable insights and structured frameworks for the integration of BIM processes with the LEED certification framework. We offer a proactive approach to support stakeholders in the AEC sector in their endeavors to enhance sustainable building practices.

2. Research Framework

To understand the pivotal role of the LEED rating system v.4.1 for "Building Design + Construction" in advancing sustainable building practices, it is essential to delve into the intricate framework of this certification program.

The LEED certification program, which originated in 1993, has evolved through multiple iterations, continuously refining its foundation for sustainable building practices. This study focuses on the specifics of the latest iteration, the LEED rating system v.4.1 for "Building Design + Construction," providing critical insights into cutting-edge sustainable building principles and standards. The decision to narrow the focus to the "Building Design + Construction" category, rather than exploring categories like "Interior Design and Construction" (ID + C) or "Building Operations and Maintenance" (O + M), aligns with the study's overarching objective: creating a comprehensive framework that seamlessly spans the various phases of the construction process.

The LEED rating system assigns points across distinct categories: "Location and Transportation", "Sustainable Sites", "Water Efficiency", "Energy and Atmosphere", "Materials and Resources", "Indoor Environmental Quality", and "Innovation", with a maximum score of 110. These categories encompass prerequisites, which are imperative conditions for achieving LEED certification, and credits, which offer flexibility and carry varying point values. The accumulation of credits dictates the certification level attained based on the final cumulative score.

The "Innovation" category introduces dynamism to the LEED system through "Pilot Credits." This experimental facet, accounting for five out of the six potential credits within this category, explores innovative strategies and practices that could be assimilated into forthcoming certification iterations. This dynamic element encourages the adoption of avant-garde solutions and fosters ongoing refinement of the LEED system, benefiting from experience and feedback.

Supplementary avenues in the LEED system comprise "Regional Priority Credits" and "Exemplary Performance Points". The former acknowledges regional nuances and requirements, enabling designers to earn additional points by tailoring solutions to local geographic, climatic, and cultural considerations. The latter acknowledges achievements surpassing the foundational LEED prerequisites, stimulating innovation and commending exceptional dedication to sustainability.

The BIM Project Execution Planning Guide (PEPG) v2.2 (2019), developed by Penn State College of Engineering [32], plays a crucial role in informing and guiding our research. This resource serves as a valuable reference point, offering a comprehensive repository of BIM uses that are directly pertinent to the construction process. The PEPG meticulously outlines essential BIM applications that align with BIM methodology, providing in-depth insights into the resources and competencies required for their effective implementation.

However, it is important to note that for addressing specific simulation requirements, the integration of additional functionalities becomes necessary. This need arises from the fact that the PEPG, while highly informative, does not encompass all potential BIM uses. Therefore, our research extends beyond the boundaries of the PEPG to explore and integrate these additional functionalities, ensuring a more comprehensive approach to BIM and sustainability integration.

3. Materials and Methods

In Phase 1 of our research, we dedicated our efforts to the development of LEED-BIM worksheets. These worksheets were meticulously crafted to provide customized guidance structures for each category within the LEED rating system v.4.1. Our goal was to create tailored frameworks that would strategically align BIM processes with LEED prerequisites and credit requirements within each category. These frameworks were designed to be interactive and dynamic, allowing for adaptability to the unique needs and requirements of specific projects. To identify the relevant BIM processes, we referred to the process execution planning guide (PEPG) [32], ensuring that our approach was well-informed.

Moving on to Phase 2, we shifted our focus to the identification of specific BIM uses that are crucial for meeting LEED prerequisites and earning credits. Building upon the foundation of the LEED-BIM worksheets, we seamlessly integrated these identified BIM uses with the existing BIM applications outlined in the PEPG. This integration process resulted in a comprehensive catalog of BIM implementations that are tailor-made for the construction process, aligning perfectly with LEED sustainability goals.

In Phase 3, we expanded upon the BIM process map template derived from the PEPG. Our aim was to cover the entire construction process, from its initial conceptualization to long-term maintenance. This involved meticulous mapping of each identified BIM use to a specific phase of the building process and assigning accountability to the relevant entity. The outcome of this phase was the creation of the Level 1 process map, which provided a visual representation of how BIM processes seamlessly integrate at various stages of construction.

Lastly, in Phase 4, we developed specific process maps that were tailored for select pilot credits sourced from the LEED rating system v.4.1 Building Design + Construction's Pilot Credits Library. Our focus was on individual BIM uses that aligned with these specific pilot credits. These process maps provided a detailed roadmap for effectively meeting these credits through the strategic application of BIM processes.

3.1. Phase 1: LEED-BIM Worksheets Development

During Phase 1 of our research, our primary objective was to seamlessly integrate sustainability considerations into the early stages of the design process. This phase focused on the development of LEED-BIM worksheets, which are essential tools for creating a proactive sustainability strategy that addresses protocol prerequisites and secures associated credits. These worksheets were meticulously designed to align with the LEED rating system v.4.1 for "Building Design + Construction", covering critical categories such as "Location and Transportation", "Sustainable Sites", "Water Efficiency", "Energy and Atmosphere", "Materials and Resources", "Indoor Environmental Quality", and "Innovation".

We made an informed decision not to create a separate LEED-BIM worksheet dedicated to "Regional Priority" credits. Although these credits hold varying degrees of significance, they essentially echo existing information. However, we did include a column within the worksheets to clearly delineate the significance of these credits, addressing the importance of these credits, including Italian regional priorities, in the research.

The "Innovation" category introduced flexibility through pilot credits, which allow designers to exercise discretion in selecting which credits to pursue, fostering ingenuity and experimentation. Additionally, opportunities for "Exemplary Performance" within specific LEED protocol credits further incentivized excellence. For instance, achieving an extra point in the C9 "Acoustic Performance" credit in the "Indoor Environmental Quality" category required meeting all three requirements, while achieving a single credit required fulfilling two criteria. This highlighted the importance of an exhaustive study of the LEED protocol, involving a comprehensive understanding of prerequisites and credits.

We emphasized the significance of an in-depth understanding of the LEED protocol, which formed the foundation for identifying the most suitable BIM uses to achieve established objectives. Simultaneously, familiarity with the project execution planning guide (PEPG) [32] was crucial, as it enabled the seamless correlation of available BIM uses with protocol prerequisites and credits—a central aim of this phase.

The LEED-BIM worksheets were designed to differentiate between the LEED rating system's prerequisites and credits, empowering designers to promptly recognize essential objectives and those offering flexibility. This structure facilitated the anticipation of the desired certification level by considering the minimum threshold required for a specific level. Consequently, the worksheets facilitated the alignment of one or more essential BIM uses with each prerequisite or credit, designating responsible parties for each sustainability-focused endeavor.

The “BIM Use” column, which housed necessary BIM uses, was primarily drawn from the project execution planning guide (PEPG) v2.2 (2019) [32], supplemented by pivotal uses integrated to fulfill specific LEED prerequisites or credits. We also relied on the BIM uses guide from Harvard University Planning and Design to correlate each LEED protocol prerequisite or credit with pertinent BIM uses.

Within the LEED-BIM worksheets, critical considerations regarding design extended to the accountability of executing the corresponding BIM use. The selection of the responsible party was based on their skill set, expertise, and experience. This approach prioritized activities and efficiently allocated resources, ensuring optimal resource utilization. It also addressed technological requirements and competencies, serving as a safeguard against goal abandonment due to resource limitations. Additionally, insights gleaned from LEED protocol analysis frequently highlighted areas requiring attention, such as supplementary documents, enabling designers to seamlessly address them throughout the process. These insights were integrated into a dedicated column within the worksheets.

In summary, Phase 1 emphasized a holistic, integrated design approach, encompassing various dimensions of sustainability, particularly the LEED rating system, from the preliminary phase of our research.

3.2. Phase 2: Integrating BIM Uses for Project Phases

In Phase 2, we focused on the integration of BIM uses for project phases, which involved a dynamic approach to align BIM practices with the LEED certification process. It is important to emphasize the innovative aspects specific to this integration, which differentiate it from traditional LEED implementation methods.

Our approach in this phase dynamically integrated essential BIM uses with those sourced from the process execution planning guide (PEPG) v2.2 (2019) for new construction building processes. Unlike static methods, this dynamic integration allowed us to adapt to project-specific needs and ensure alignment with LEED prerequisites and credits.

We created a coherent visual diagram that categorized integrated BIM uses according to specific phases of the construction process. This diagram provided a comprehensive visual representation of BIM applications throughout the building process, making a clear distinction between general BIM model uses and LEED BIM model uses. This differentiation was crucial for effectively integrating the LEED protocol into BIM process maps.

Ensuring alignment between the BIM uses listed in the LEED-BIM worksheets and the summarized diagram was pivotal. This alignment guaranteed the consistency of information, preventing data loss and optimizing the likelihood of achieving the desired outcomes. Establishing connections between BIM uses was a fundamental preparatory step for developing subsequent BIM process maps.

Understanding the interrelationships between BIM uses involved determining when one use started in relation to another and when it concluded. This comprehension was particularly relevant when certain uses spanned multiple phases or required concurrent processes. These intricacies were unique to the dynamic nature of BIM and its capacity to support real-time collaboration and information exchange.

3.3. Phase 3: Level 1 Process Map Development

In Phase 3, our focus shifted to the development of a BIM process map, a crucial component within the BIM execution plan (BEP) tailored for BIM design. The primary purpose of this process map is to provide planners with a comprehensive overview of the entire building process, ensuring seamless alignment with the five phases defined earlier and depicted in the BIM uses diagram.

As mentioned previously, a single BIM use may evolve into distinct processes, each with varying nomenclature and responsibilities as the phases progress. During the design phase, it was essential to ensure that each pre-identified use, from both the worksheets and the uses diagram, correlated with one or more referenced processes. Additionally, to avoid confusion, if certain uses were recurrent throughout the process, they should never fall within the same phase.

To initiate the development of the process map, we began with a template sourced from the process execution planning guide (PEPG). This template was expanded and enriched by integrating BIM uses derived from the diagram created in Phase 2. The use of a standardized language adopted from the PEPG was essential for universal comprehensibility.

An important distinction made at this stage was between the language governing the workflow of internal process activities and the language dictating information exchange. A process map should not only delineate activity sequences and assign responsibilities but also elucidate information exchange. Clear, shared language minimized errors and information loss. Therefore, ensuring the coherence of information concerning outputs across various activities, as outlined in the LEED-BIM worksheets when tied to the LEED rating system, was paramount in this phase. Additionally, indicating the levels of detail (LOD) for model deliveries at different phases proved valuable in setting construction process milestones.

The conceived process map took the form of a sequence of activities, interlinked based on sequential logical relationships (Figure 2). We adopted a legend provided by the PEPG to ensure clarity and consistency in visual representation (Figure 3).

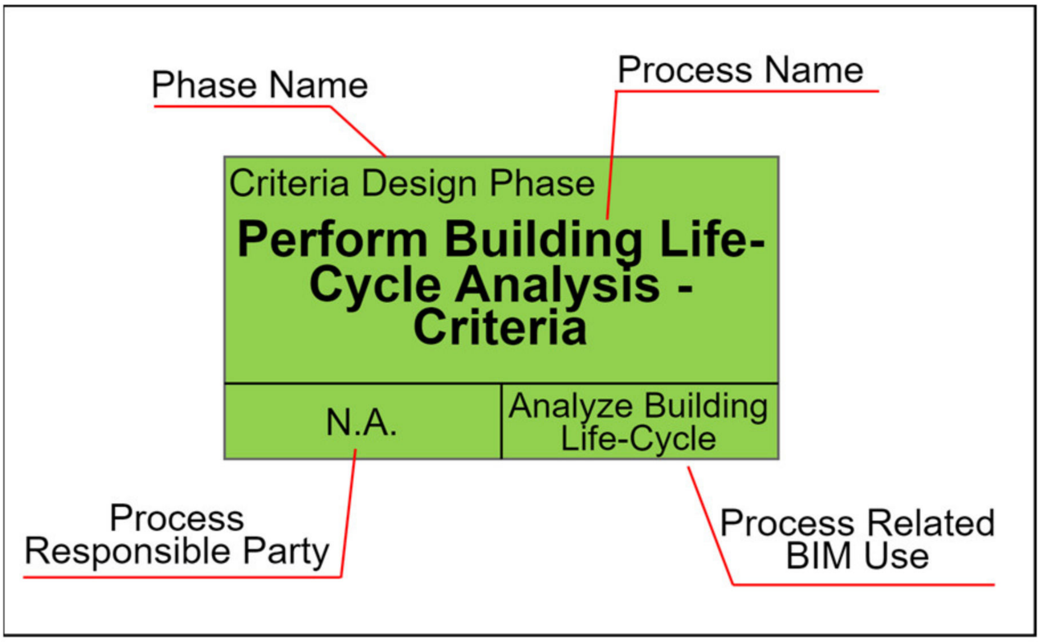
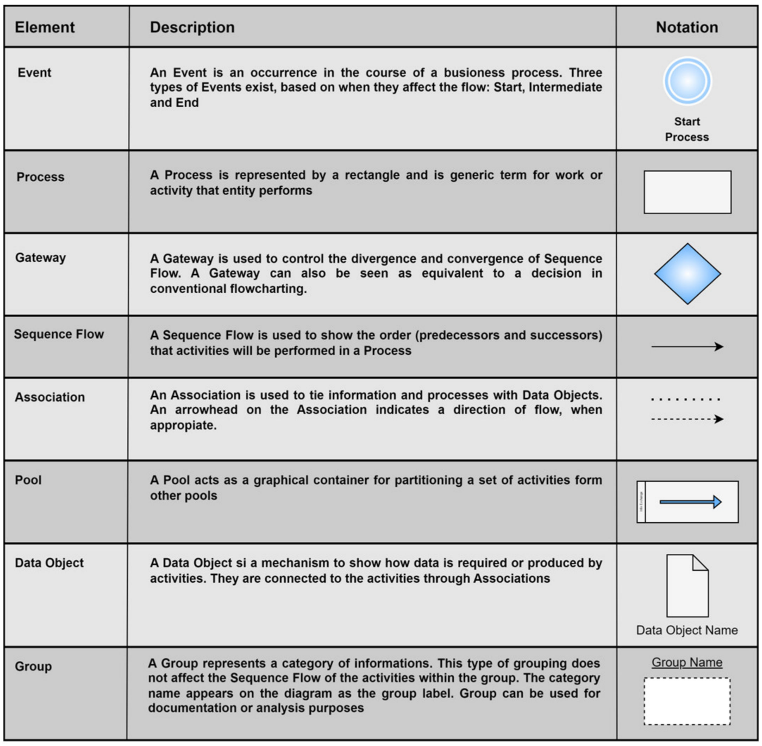


Figure 2. Single activity of the BIM process map, the perform building life-cycle analysis criteria process is shown as an example.

The process map template crafted within the PEPG was realized using an open-source tool named Diagrams.net. This tool was also used for formulating the maps in Phase 3 and Phase 4. It is worth noting that this map functions as a customizable template adaptable to designers' requirements. This user-friendly and accessible tool facilitates modifications to the template, allowing for personalized adjustments by designers.



Element	Description	Notation
Event	An Event is an occurrence in the course of a busioness process. Three types of Events exist, based on when they affect the flow: Start, Intermediate and End	Start Process
Process	A Process is represented by a rectangle and is generic term for work or activity that entity performs	
Gateway	A Gateway is used to control the divergence and convergence of Sequence Flow. A Gateway can also be seen as equivalent to a decision in conventional flowcharting.	
Sequence Flow	A Sequence Flow is used to show the order (predecessors and successors) that activities will be performed in a Process	
Association	An Association is used to tie information and processes with Data Objects. An arrowhead on the Association indicates a direction of flow, when appropiate.	
Pool	A Pool acts as a graphical container for partitioning a set of activities form other pools	
Data Object	A Data Object si a mechanism to show how data is required or produced by activities. They are connected to the activities through Associations	Data Object Name
Group	A Group represents a category of informations. This type of grouping does not affect the Sequence Flow of the activities within the group. The category name appears on the diagram as the group label. Group can be used for documentation or analysis purposes	Group Name

Figure 3. Process mapping notation for BIM process maps.

3.4. Phase 4: Level 2 Process Maps Development

In Phase 4, we dedicated our efforts to the development of Level 2 (Liv.2) process maps, representing the culmination of our research. These maps are meticulously crafted for individual BIM use(s) identified within the process, providing intricate details on the sequence of processes required for their optimal utilization. What sets these maps apart is that they pertain not only to specific BIM use(s) but also to the distinct credit being pursued within the LEED certification. One map can encompass one or more BIM uses simultaneously, and it can be tailored to achieve one or more LEED credits concurrently, especially when similar procedures are required.

The Liv.2 maps delve into deeper technical intricacies of the building process and are highly specialized in nature. Consequently, they could not originate from a template provided by the PEPG. Nevertheless, in terms of their overarching structure, these maps align with the language and symbology prescribed by the guide, which we have adhered to thus far.

Like the Liv1 maps, these Liv.2 maps take the form of a sequence of interconnected activities, linked by logical sequential relationships. Figure 4 provides an example of an individual unit within the Liv.2 process, specifically the "Exporting Model to Acoustic Analysis Application" process.

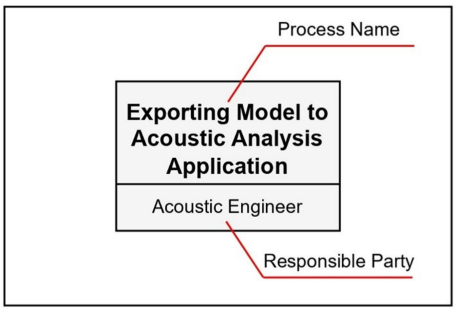


Figure 4. Single unit of the Liv.2 process: the Exporting Model to Acoustic Analysis Application process is shown as an example.

Unlike the single-process maps in Level 1, the Liv.2 maps do not include the phase name since they relate to a single BIM use that may span multiple phases. Additionally, the associated BIM use is not explicitly indicated, as the entire process map pertains to one (or two) BIM uses. Each activity in the map identifies the accountable individual, placed at the bottom.

To enhance the effectiveness of these maps, we introduced a symbol denoting a verification stage for results obtained post-simulation or analysis. In this stage, the outcomes must meet performance criteria for approval. Additionally, as these are specialized procedures tailored for specific credits, each map includes a supplementary section containing comprehensive instructions for executing the required operations.

The choice of credits (and, consequently, BIM uses) for which these Liv.2 maps were created was arbitrary and made by our research. These particular BIM uses are deemed crucial for achieving pilot credits, which we consider pivotal. These credits, although modest, play a significant role in advancing scientific research toward the realization of sustainable buildings and harnessing the potential of the LEED rating system during its "pilot phase."

4. Results

4.1. Phase 1: LEED-BIM Worksheets

The implementation of the LEED-BIM worksheets in Phase 1 of our research has yielded significant insights that warrant further exploration and interpretation within the context of existing research and our initial hypotheses. These findings have wide-ranging implications and invite deeper investigation.

The LEED-BIM worksheets, designed as versatile tools, have proven particularly advantageous in the early phases of formulating sustainable strategies for energy certification. Originally tailored for the LEED rating system v4.1 in Building Design + Construction, these templates have demonstrated adaptability across diverse LEED protocol rating systems.

These worksheets offer advantages that extend beyond the preliminary phase, serving as documents akin to the BIM execution plan (BEP). They explicitly outline roles and responsibilities specific to the LEED rating system. Articulating these roles within a sustainable building process can enhance overall performance outcomes. Moreover, the worksheets facilitate the assessment of capability ratings for individuals responsible for BIM uses, averting potential goal misalignment due to skill deficiencies. The incorporation of capability ratings aids in preempting potential misalignments by assessing the preparedness of individuals responsible for executing specific BIM uses. This proactive approach minimizes the risk of insufficiently addressed tasks. The worksheets also aid in gauging the resources and competencies required for a given prerequisite or use, ensuring adequacy for task execution.

One notable capability of the LEED-BIM worksheets is the early estimation of potential certification levels that a building could attain. By conducting an arithmetic calculation of pursued credits, an initial assessment of the project's certification standing can be derived. The inclusion of a regional priority column further underscores the importance of pursuing specific credits while accommodating geographical considerations.

Examining a specific example, the LEED-BIM worksheet for indoor environmental quality reveals its underlying structure and functionality. It systematically organizes information, categorizing between prerequisites (mandatory for certification) and credits (providing flexibility). The worksheets align each activity with a corresponding BIM use designated by PEPG v2.2 (2019) and quantify the credit's importance during the design phase. The inclusion of a regional priority column allows for customization based on location, enhancing regional relevance.

Transparent role identification and allocation are crucial aspects facilitated by the LEED-BIM worksheets. The "Responsible Party" and "Value to Responsible Party" columns outline the responsible individual's role and the significance of the BIM use for them. Explicitly defining roles within a sustainable building process amplifies performance outcomes by fostering accountability and cohesion. This transparency aligns team members with their respective responsibilities, facilitating streamlined collaboration. Roles are further assessed in terms of available resources, competency, and experience, as outlined in the "Resources Required" and "Competencies Required" columns.

The inclusion of a "Notes" column provides a repository for pertinent observations during the LEED rating system study, often related to location-specific considerations or alternative paths or options to obtain the credit.

While the innovation category's credits were chosen arbitrarily, they illustrate the flexibility of the LEED protocol. Moreover, the study highlights the potential for synergies between credits spanning multiple categories. For instance, the C9 acoustic performance credit, identified as a regional priority, illustrates the possibility of harnessing bonus points through cross-category alignment. Furthermore, synergies between credits across categories can lead to amplified points through exemplary performance and pilot credits.

The comprehensive analysis of the LEED-BIM worksheets solidifies their foundational role as indispensable tools in sustainable design. They underpin transparent communication, accurate estimation, and meticulous planning for LEED certification. These findings lay the groundwork for a deeper exploration of the subsequent phases, which intricately integrate these worksheets within a methodological framework for seamless BIM process mapping and sustainable construction.

4.2. Phase 2: Associate BIM Uses for Project Phases

The "BIM Uses for Project Phase" diagram in Figure 5 plays a pivotal role in bridging the development of the LEED-BIM worksheets and the creation of Level 1 process maps. This diagram serves as a crucial tool for identifying interdependencies between different BIM uses and for linking specific processes to each use. It acknowledges the dynamic nature of BIM uses and processes, where a single use may span multiple phases, and processes associated with a use may evolve, changing phases, objectives, names, or responsible parties.

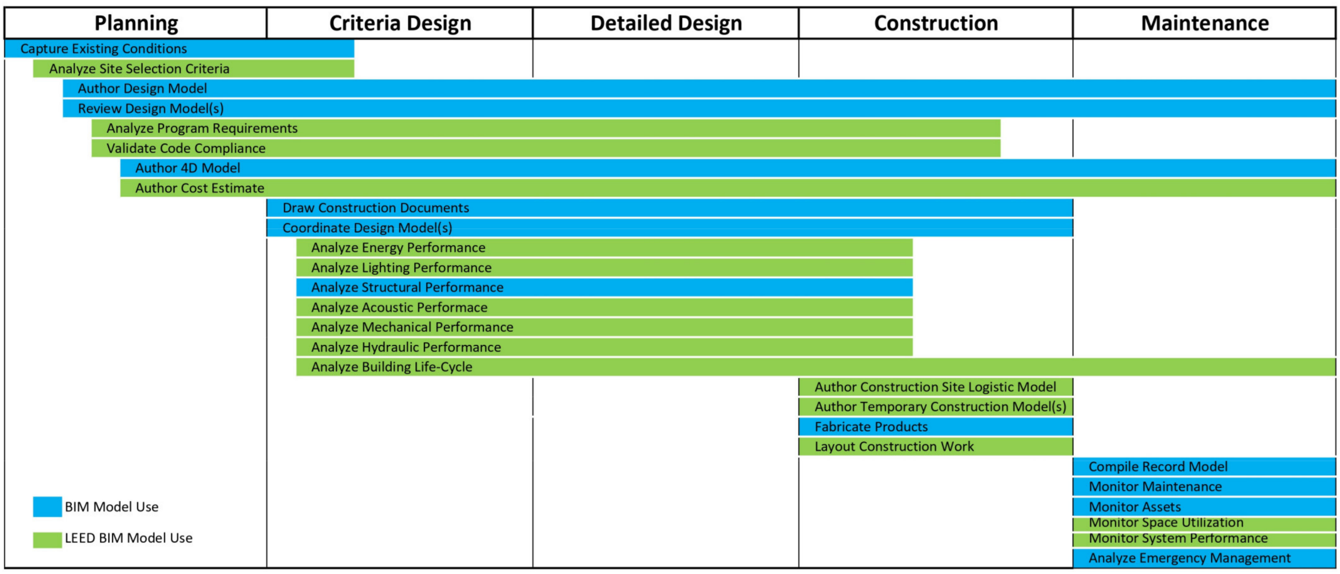


Figure 5. BIM uses for project phase.

One of the key functions of this diagram is to validate the coherence between processes and uses across various phases. For example, if a specific BIM use (e.g., author cost estimate) is indicated in all five phases on the diagram, it should correspond to five distinct processes, each aligned with a specific phase of the building process. This validation ensures that there is no information loss and maintains the integrity of process mapping.

Additionally, the diagram seamlessly integrates with the LEED-BIM worksheets by incorporating every identified use from the worksheets. These uses are highlighted in green on the diagram to emphasize their critical role in achieving LEED certification. Conversely, other BIM uses, which may not be imperative for LEED certification, are sourced from PEPG v2.2 (2019) and are indicated using blue shading.

It is important to note that this "BIM Uses for Project Phase" diagram does not represent a chronological program with specific timeframes. Instead, it provides a tool to understand the temporal interplay and interdependencies among various BIM uses across project phases. While the study suggests the possibility of harmonizing this diagram with a chronological program to add a temporal dimension, it emphasizes the indivisible connection between this diagram of uses and the forthcoming Level 1 process map.

Overall, the "BIM Uses for Project Phase" diagram, in conjunction with the Liv1 process map, serves as a critical foundation for advancing the synergy between BIM processes and LEED certification in the subsequent phases of the research. It helps ensure that BIM uses are appropriately aligned with project phases and sustainability objectives, paving the way for the development of comprehensive process maps.

4.3. Phase 3: Liv1 Process Map Development

The development of the "Liv1 Process Map" represents a significant milestone in this research endeavor (Figure 6). This visual representation encapsulates the entire new construction building process, providing a holistic view of the project's lifecycle. The Liv1 process map serves a dual role by incorporating responsible parties for individual processes and intricately weaving in specific BIM uses. This comprehensive perspective aligns seamlessly with the core objectives of the research.

One of the essential aspects of the Liv1 process map is its envisioned integration within building execution plans (BEPs). This integration enables dynamic interplay, allowing designers to incorporate the map as a templated resource that can be customized to align with the unique requirements of their projects. This iterative refinement process is in line with the foundational principles laid out by the LEED-BIM worksheets and the BIM uses diagram, ensuring that the Liv1 process map translates effectively into actionable insights for sustainable design and construction practices.

The "Info Exchange" segment within the Liv1 process map plays a crucial role in facilitating seamless communication among stakeholders. This segment ensures that vital data and knowledge are exchanged effectively throughout various project phases, enriching collaborative efforts and amplifying the integrity of the Liv1 process map.

Additionally, the Liv1 process map strategically incorporates the concept of level of development (LOD), which delineates the evolving detail and accuracy of project models across different phases. These LOD designations are tailored to align with the project's developmental stages, providing clarity on the level of detail required at each phase.

The organization of processes within parallel columns within the Liv1 process map optimizes visual presentation, conveying the sequential flow of activities within each process. The map emphasizes the importance of coherence across phase-specific deliveries, ensuring that BIM uses are appropriately integrated into project phases and sustainability objectives.

The Liv1 process map serves as a dynamic bridge between theoretical constructs and practical application, aligning with the core objectives of the research. It reflects the intricate tapestry of model uses across the project's lifecycle and captures the high-level exchanges of information that occur during the BIM process.

The use of color-coding in the Liv1 process map, where blue processes denote those integral to construction and green processes contribute to both construction and LEED certification, provides visual clarity. The map also uses continuous arrows to illustrate the chronological progression of activities.

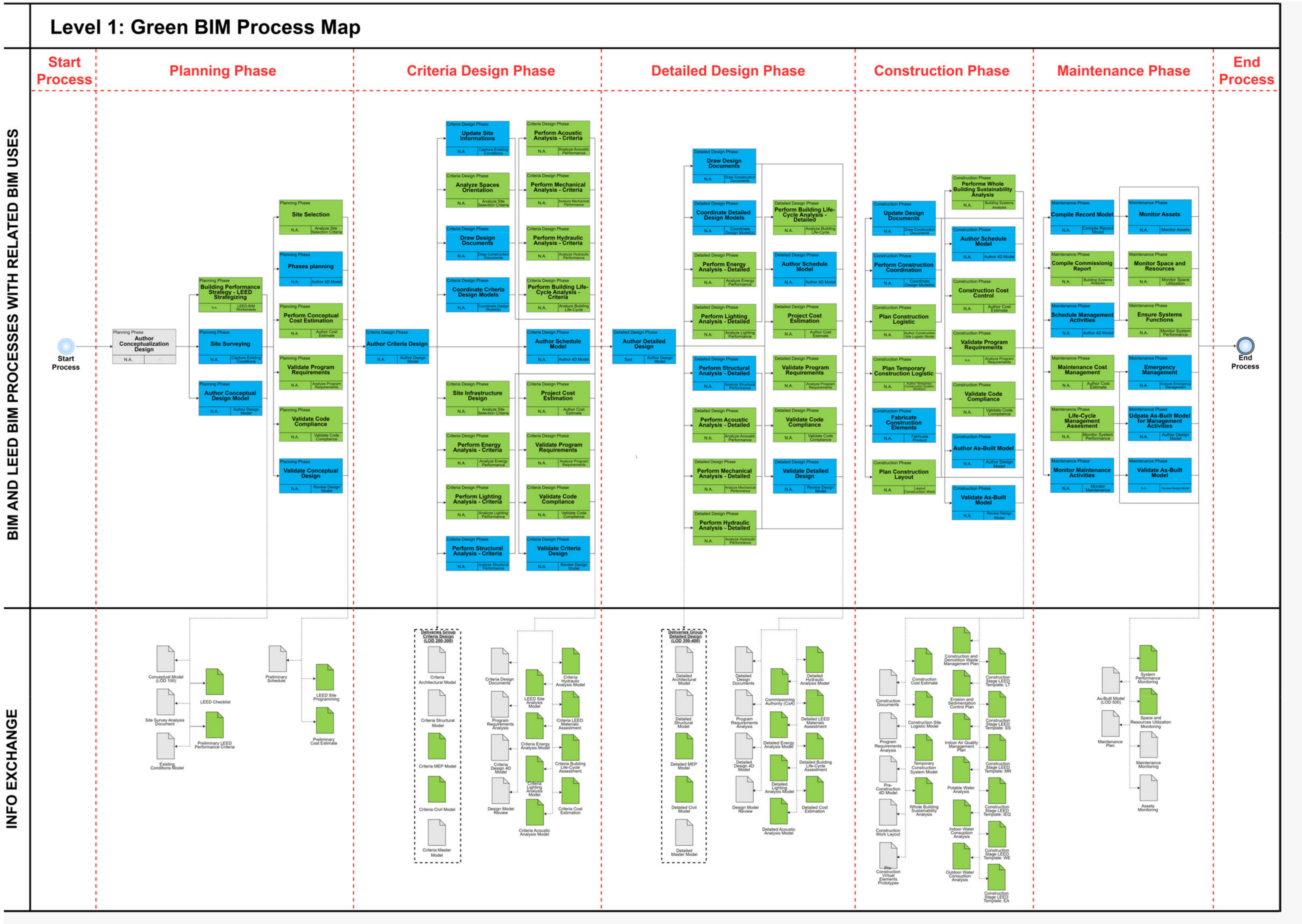


Figure 6. Liv1 BIM process map.

Red dashed lines partition the map according to distinct phases, with the primary pool representing "BIM and LEED BIM Processes" and their corresponding BIM uses. The "Information Exchange" pool serves as a nexus, harmonizing the flow of essential data. This map reinforces the importance of coherence across phase-specific deliveries and aligns with insights derived from the LEED rating system, strengthening the connection between protocol-driven output requirements and data objects.

The introduction of group notations in later phases, such as 'Deliveries Group Criteria Design' and 'Deliveries Group Detailed Design,' highlights the specification of the level of development (LOD) and its reflection of project phases.

Overall, the Liv1 process map demonstrates the viability of coherence across phase deliveries and highlights the harmonious interplay cultivated through this research, enhancing the efficacy and precision of sustainable design and construction strategies.

4.4. Phase 4: Liv.2 Process Map Development

Phase 4 represents the culmination of this research, presenting the "Liv.2 Process Map" as a significant milestone. This phase involves a thorough analysis of the results and their implications within the context of previous studies and working hypotheses, as well as the exploration of potential avenues for future research.

The Liv.2 process map builds upon the foundation established by the Liv1 process map and introduces a third horizontal pool labeled "Reference Information". This pool serves as a repository for structured information resources from internal and external sources, aimed at supporting managerial decisions and fulfilling prerequisites for executing BIM uses. It is distinct from the "Info Exchange" pool, which primarily manages the flow of BIM deliverables across processes.

A key element introduced in the Liv.2 process map is the "gateway," represented by an angled square. This symbol serves as a checkpoint for evaluating sequence flow convergence and divergence and plays a pivotal role in the analysis and verification of the simulation outcomes. Positive simulation results lead to the progression of processes, while unfavorable outcomes prompt revisitation and refinement of the design phase.

The Liv.2 process map incorporates selected BIM uses from the LEED rating system v4.1 Building Design + Construction Pilot Credits Library. Examples of integrated BIM uses include "Analyze Acoustic Performance", "Analyze Program Requirements", "Author Construction Site Logistic Model", "Author Cost Estimate", and "Analyze Hydraulic Performance". These BIM uses are intricately linked with LEED credits, demonstrating their adaptability and versatility across multiple processes and design phases.

Figure 7 visually presents the Liv.2 BIM process map for the "Analyze Acoustic Performance" BIM use, aligning it with specific LEED credits. This map highlights the successful fulfillment of requirements for credits such as "Acoustic Performance" and "Enhanced Acoustic Performance—Exterior Noise Control", showcasing how integrated BIM processes can effectively contribute to achieving sustainability goals.

While the Liv.2 process map emphasizes the interplay between BIM processes and the attainment of LEED credits, it does not delve into the technical intricacies of BIM software interoperability, data standards, and data sharing protocols. Future research endeavors may focus on these technical aspects to facilitate smoother data exchange between stakeholders and BIM software platforms, ultimately enhancing collaboration and efficiency in utilizing BIM processes for sustainable design and construction objectives.

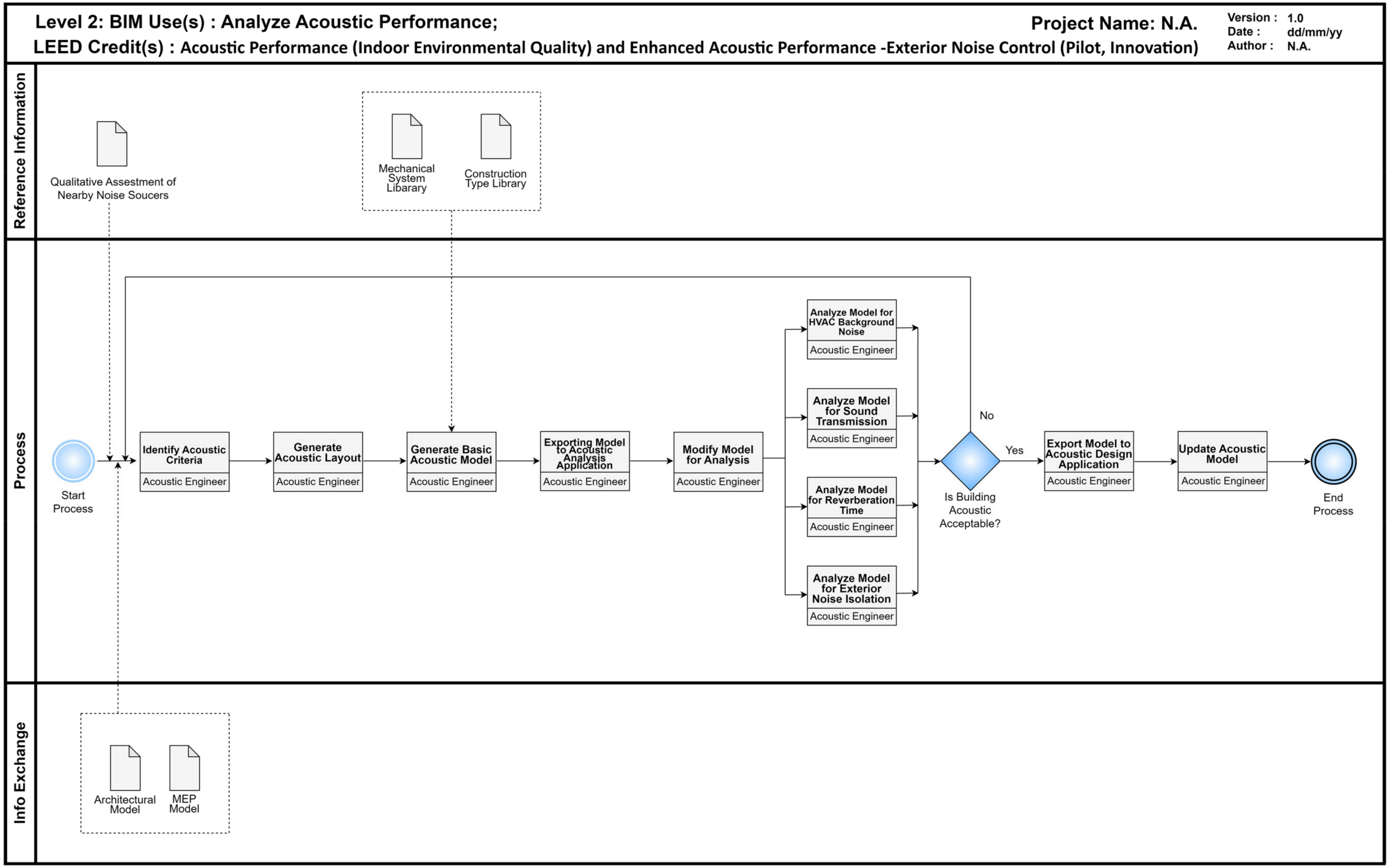


Figure 7. Liv.2 BIM process map; BIM use(s): analyze acoustic performance; LEED credit(s): acoustic performance (indoor environmental quality) and enhanced acoustic performance—exterior noise control (pilot, innovation).

5. Discussion

In this discussion section, the research outcomes are compared with related studies that address similar challenges in integrating building information modeling (BIM) with sustainability certification systems. The goal is to highlight common issues and offer insights to guide future research and practical applications.

Gandhi and Jupp [20] conducted a study on the utilization of BIM within the Green Star rating system in Australia. They emphasized the crucial role of BIM in achieving sustainability certifications and identified challenges. One significant finding was the gap between the potential certification credits achievable through BIM and the actual credits obtained. This emphasizes the need for more detailed object information in simulation models. In contrast, this research focuses on flexible integration with the LEED rating system, allowing professionals to choose tools aligned with their expertise.

Zanni [21] used the IDEF3 functional modeling method to create a BREEAM strategy diagram harmonized with RIBA plan of work stages. Their work addressed integration challenges between BREEAM and BIM processes, with a focus on specifying the level of development (LOD) for each project phase. While valuable, this research goes beyond specific variables and covers the entire project lifecycle, from conceptualization to maintenance. It emphasizes the flexible integration of sustainability criteria without prescribing particular tools.

Salgueiro and Ferries [22] outlined a methodology to integrate the BREEAM and LEED rating systems within a unified BIM process map. Their research concentrated on the convergence of these two systems but demonstrated the adaptability of their framework to various sustainability objectives. The Liv.2 maps developed in this research align with the specificity of their results, and the potential universality of BIM process mapping for diverse sustainability goals is acknowledged.

In summary, these related works provide valuable insights into the challenges and opportunities of BIM sustainability integration. This research contributes by offering a flexible and dynamic approach to integrating the LEED rating system with BIM processes, ensuring relevance across a wide range of sustainability certification objectives. The findings highlight the importance of aligning sustainability and BIM to streamline design, empower informed decision-making from project inception, and foster the creation of energy-efficient and ecologically conscious buildings. The synthesis of LEED-BIM worksheets and the establishment of precise BIM uses for sustainability credits showcase BIM's capacity to steer certification goals. The developed Liv1 and Liv.2 maps provide designers with comprehensive insights into processes, delineating activities and responsibilities while facilitating information exchange. Moreover, the amalgamation of BIM and sustainability principles cultivates collaborative design practices, augments building lifecycle management, and contributes to crafting resilient built environments for the future.

5.1. Limitations

It is important to acknowledge the limitations of the research to provide a clear understanding of its scope and potential areas for improvement. Here are the limitations identified in the study:

1. Theoretical Representation vs. Practical Application: There is a risk of the research's theoretical representation of BIM processes and uses diverging from practical application. While efforts were made to minimize this risk by adopting an existing template, some subjectivity may still be present.
2. Absence of Time Variable: The research does not incorporate a time variable in the representation of BIM processes and uses. This omission means that the duration of processes is not considered, potentially leading to inconsistencies between theory and practice. Future research could explore the temporal dimension to enhance accuracy.
3. Technical Aspects of BIM Interoperability: The study does not delve into the technical aspects of BIM interoperability, data standards, and data exchange protocols. These

technical factors are crucial for the seamless exchange of information between different BIM software platforms and stakeholders.
4. Limited Scope: The research primarily focuses on the building process up to LEED certification. It excludes subsequent phases such as redevelopment, decommissioning, or demolition. Expanding the scope to include these phases could provide a more comprehensive analysis of sustainability in the entire building lifecycle.

Addressing these limitations in future research endeavors can further enhance the understanding and practical application of integrating BIM processes with sustainability certification systems.

5.2. Future Developments

The future developments and potential areas for further research outlined in this section demonstrate the research's commitment to continuous improvement and practical applicability. Here are the key future directions highlighted:

1. Validation in Real-World Case Studies: Applying the Liv1 and Liv.2 process maps in real-world case studies could validate their effectiveness. This might involve comparing anticipated LEED certifications derived from LEED-BIM worksheets with actual building certifications, providing valuable insights into their practical utility.
2. Feedback from Industry Professionals: Seeking feedback from industry professionals who use these tools could help refine and enhance their effectiveness. Industry input can provide valuable real-world perspectives and identify areas for improvement.
3. Examination of Leading Green Building Companies: Analyzing the design strategies of leading green building companies in the context of the research's results could offer insights into best practices and innovative approaches to BIM sustainability integration.
4. Integration of Uses Diagram with Chronological Program: Exploring the integration of the developed uses diagram with a chronological program in a practical case study could provide valuable insights into the temporal dimension of BIM sustainability integration.
5. Exploration of Different Sustainability Assessment Methodologies: Investigating the integration of different sustainability assessment methodologies with BIM process mapping could open new avenues for research and practice, allowing for flexibility in addressing diverse sustainability goals.
6. Integration of Digital Twins, AI, and ML: The potential integration of digital twins, artificial intelligence (AI), and machine learning (ML) in enhancing the accuracy and efficiency of BIM sustainability integration represents an exciting trajectory for further exploration. These technologies can contribute to data-driven decision-making and predictive sustainability outcomes.

In summary, this research lays the foundation for practical applications and further investigations in the field of BIM-sustainability integration. By addressing these future developments and continuously refining the tools and methodologies, the research aims to contribute to the creation of environmentally conscious and resilient built environments, ultimately benefiting society for generations to come.

6. Conclusions

In summary, this research has made significant contributions to the integration of BIM technology and sustainability goals in the context of LEED certification:

1. LEED-BIM Worksheets: The development of LEED-BIM worksheets provides a valuable resource for professionals seeking to align BIM processes with LEED prerequisites and credits. These worksheets offer detailed information about responsible parties, resource requirements, and competencies needed for successful LEED certification.
2. Design Stage BIM Uses: The identification of relevant BIM uses during the design stages emphasizes their importance in achieving LEED certification. This research highlights the critical role of BIM in sustainable design and construction.

3. Comprehensive Process Map: The creation of an extensive process map that spans from initial conceptualization to maintenance stages enhances clarity and comprehensive planning. This map serves as a valuable reference for industry professionals seeking to navigate the complex landscape of sustainable design and construction.
4. Pilot Credit Maps: The development of specific maps for securing LEED rating system pilot credits promotes innovation in sustainability integration. These maps offer guidance on achieving credits that are pivotal in advancing sustainable building practices.

However, it is important to recognize certain limitations, including the need for practical validation of the proposed frameworks, considerations of temporal aspects in process mapping, and further exploration of technical aspects related to BIM interoperability.

In conclusion, this research provides a structured framework for professionals in the field of sustainable design and construction to align their BIM processes with LEED certification goals. These tools and methodologies offer a valuable resource for enhancing practices and contributing to the creation of a more sustainable built environment.

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Abbreviations

AEC	Architecture, Engineering, and Construction
BIM	Building Information Modeling
LEED	Leadership in Energy and Environmental Design
BEPs	Building Execution Plans
LOD	Level of Development
RIBA	Royal Institute of British Architects
EAM	Environmental Assessment Methodology
AHP	Analytic Hierarchy Process
PEPG	BIM Project Execution Planning Guide
ID + C	Interior Design and Construction
O + M	Building Operations and Maintenance
BREEAM	Building Research Establishment Environmental Assessment Methodology

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