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The prototypologycal design of the green responsive system. Method and tools to improve circularity and physical performances of the liminal space in the Mediterranean urban areas

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Abstract. In being aware of certain factors as the increasing of the pollution levels, the effects of the Urban Heat Island, or all the extreme climate events attributable to the constant increasing of CO_2 emissions. This paper intends to propose an innovative approach to design systems and components that allow to adapt the built environment and mitigate the effects of the Climate Change in the urban Mediterranean areas. An experimental investigation at the building scale was conducted to study the environmental aspects in the early design phase that incorporate circular and ecological materials. The physical interactions between the built and the natural environment is enhanced with the upcycling design of the "Liminal Space" through the prototypological model for the "Green Responsive System". The focus on the LS needs to push the technological definition beyond the concept of building envelope, just as the element of internal/external separation. The LS is where the "Advanced Circular Design" model can improve with the design of the GRS all the technological elements of adiabatic nature. The proposed framework enables the GRS to have a dynamic and systemic answer to the extreme change of the climatic situation in order to have a strong impact on the performance related to the environmental aspects. The parametric tools in the ACD model offers an important digital interface that can include all the regenerative requirements of the entire building considering the embodied CO_2 emissions, the production and the energy consumption during the operational phase, and at the same time to control and improve the recyclability of all its components. The structure of the paper is presented as a succession of digital and physical design processes that identify all the phases for the definition of the GRS when it works on the LS. This becomes a central node in the development of the methodological framework for the upcycling design and the digital control of the responsiveness in the technological systems used for the integration of the physical aspects and the digital devices by using circular materials.

Keywords: Additive manufacturing / green responsive system / liminal space / regenerative design / upcycling

1 A proposal for frontier research: upcycling liminal space

The present study delves into experimental steps that address multiple theoretical queries, leading to noteworthy outcomes. The Green Responsive System (GRS) emerges as an instrumental cognitive and evolutionary tool (prototypology) for charting paths in frontier research. This sets the stage for a gradual transition, detailing how these overarching sustainable principles are vital in the specific design and functionality of a particular component the Liminal Space (LS). This approach establishes a context for the detailed analysis that follows, illustrating a clear progression from general sustainable design methods to the focused development of the LS. This exploration incorporates new five paradigms, seamlessly woven into the subsequent descriptions:

- **Advanced sustainable design.** This approach focuses on 'jumping scale' to enable regenerative and ecological design at both urban and system component scales. It represents a proactive response to environmental challenges, emphasizing regeneration over mere sustainability.
- **Climate change adaptation.** Design considerations now include climate change effects, with a focus on creating systems and devices that contribute to CO_2 storage and decarbonization. This involves tackling cycle waste impacts and promoting upcycling, particularly at the end of a product's life.

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- **Site-specific solutions.** There's a growing emphasis on experimenting with solutions tailored to specific sites, creating reference workflows adaptable to various physical-climatic and design contexts. The Mediterranean region, with its unique temperature range, serves as a model for studying system resilience and adaptation responses.
- **Emerging technologies in design.** Design processes are increasingly incorporating emerging technologies, with prototyping as a critical step in validating technological maturity (TRL). This approach involves the strategic use of open data and digital tools like additive manufacturing, ensuring controlled information flow and fostering radical innovation.
- **Open knowledge platform.** The development of an open knowledge platform facilitates the transfer and exchange of information and experiences. Despite its complex language, this kind of platform aims to produce traceable outcomes, enhancing the integration of research findings into educational contexts.

Advanced Sustainable Design is explored as an approach to "jumping scale", aiding regenerative design and responding to ecological design transitions at the urban and system component scale. This involves tackling design issues with a keen eye on climate change effects. The focus here is on local and global system transitions, emphasizing the creation of devices capable of CO_2 storage (neutrality). This approach significantly contributes to decarbonization and mitigates the impacts of waste cycles and end-of-life scenarios through upcycling.

The study also underscores the necessity of experimenting with "site-specific" solutions to establish reference workflows. These workflows are transferable to various physical-climatic and design contexts. The Mediterranean area is highlighted as a "climate spot," offering unique temperature range conditions for studying system resilience and adaptation responses.

Innovation in design processes towards emerging technologies is a central theme. This innovation necessitates the use of prototyping as an integral part of validating Technological Readiness Level (TRL). It involves a detailed focus on each step, encompassing the use of open data and digital tools, such as additive manufacturing. This approach is pivotal for controlling information flow, which is directly related to the material and immaterial resources significant for radical innovation.

Furthermore, the study introduces the concept of an "open knowledge platform." This platform is envisioned as a conduit for information and experience exchange. Its advancement yields traceable results, despite the complexity of its language. The readability of its narrative spaces is traced in the research experiences transferred to teaching. Digital practices and optimization processes are employed in experimenting with the Liminal space, a prototype for constructing modules and systems for vertical greening. This is designed to enhance ecological transitions in the built environment.

The "Green Responsive Model" [1] (GRM), within an Advanced Circular Design (ACD) process, re-interprets solutions for ecological optimization. It employs a technological system to create vertical and horizontal closures of casing and components integrated into urban spaces. This offers high ecological performance, moving the concept of the building envelope towards the "liminal space" definition. This space acts as an industrial component, facilitating interactions between the building and its third environment. The envelope's border assumes a "liminal" function, designing natural spaces and corridors with a multi-scalar approach. These considerations include the energy efficiency of the GRS, reduction of energy consumption, pollution rate decrease by removing air pollutants, and highlighting the benefits of green shaping at both urban and building levels. The ecological performance is underscored by factors such as solar radiation interception, thermal insulation from vegetation and substrate, evaporative cooling through evapotranspiration, and the modification of wind effects on the building.

2 State of the art

This study offers a thorough review of various technological devices and responsible system configurations that enhance performance in energy saving and CO_2 storage, while minimizing CO_2 emissions during the production stage. It focuses on components and systems used in offsite construction industry production. Theoretical aspects are highlighted to provide a scientifically grounded background in regenerative design [2].

A range of software now exists for managing data on building consumption and emissions in the built environment. This software addresses all aspects in a parametric manner, providing specific proof through design-driven optimization.

Historically, building operations and embodied emissions have been integrated within the Liminal space, achieving indoor and outdoor thermal comfort through common sense and tacit knowledge. This study extends the discussion to the practical application of experimental sustainable design principles [3]. It begins with an overview of technological devices and systems that contribute to energy efficiency and CO_2 reduction on a broad scale. A practical example of is CO-MIDA, a 3D printed ceramic green wall developed at IAAC facilities [4]. This "technological Nature Based Solution" combines ecological performance through physical processes and cyber systems. Its creation depends on several factors: bio-photovoltaics for energy generation and storage, robotic additive manufacturing for novel material production and mass customization, responsive design for site-specific adaptation, and system monitoring and optimization through sensor networks, cloud computing, and machine learning software.

The design process leverages modeling and simulation tools to collect and analyze data during the early design phase. Testing focuses on the interaction between lighting conditions and the geometric configuration of the reactors. Within the Green Responsive Model, the Jumping scale effect influences the taxonomy of components and codes their language, facilitating an evolutionary approach with computational methodologies and tools. Grasshopper's parametric space, manipulated using plugins like LadyBug and HoneyBee, reports on the performance status of the experimentation object. These tools analyze both the endogenous aspects of the component/system (HoneyBee) and the environmental aspects related to the experimentation scenario (Ladybug) [5], allowing for accurate performance simulations. Due to limited references on transferring circular economy principles into numerical parameters, the study's results Life Cycle Assessment (L.C.A.) using Grasshopper plugins like Bombyx 2.0.

3 Methodological approach

In this section, the paper transitions from a broad exploration of the ACD model to a more concentrated focus on the LS. Initially, it discusses the role of parametric tools in enhancing sustainability within the ACD framework, providing a general overview of how these tools contribute to sustainable design. As the discussion progresses, it becomes more specific, illustrating the application of these tools in the design and assessment of individual building components [6]. This part of the paper particularly highlights how these sustainable design principles are applied in the lifecycle analysis and environmental impact assessment of the Liminal Space, a key component in sustainable architectural design. This progression from general methods to specific applications effectively demonstrates how broad sustainability concepts are realized in the detailed design of a specialized component like the LS.

In the ACD model, parametric tools provide a vital digital interface to enhance sustainability assessment methods. This framework incorporates regenerative requirements for entire buildings, addressing embodied CO_2 emissions, production, operational energy consumption, and recyclability of components.

An experimental analysis in the Sustainable Innovation Design course demonstrated correlations between circular design practices and regenerative aspects in the Grasshopper environment. By adding parametric evaluation tools to the performative tools, the proposed approach aims to demonstrate that a sufficient comparison can be made for the optimization of the parts in an advanced circular perspective already during the early design phase [7]. Regenerative processes in responsive optimization of building components and systems naturally evolve from performance-based design approaches in a parametric setting. By integrating parametric evaluation tools with performative tools, our approach aims to facilitate early design phase comparisons for optimizing components within an advanced circular framework.

Future efforts will focus on including all technological devices and formal configuration systems capable of enhancing performance as carbon dioxide storage units. This will be achieved by minimizing life cycle impacts and capturing and disposing of emission rates [8].

4 The proto-typological design of the green responsive system

Heisel and Hebel introduce the concept of proto-typology [9], a significant paradigm shift in the use and innovation of construction materials. This term, a blend of "prototype" and "typology," signifies the application of full-scale models to enhance sustainability and resource efficiency in construction.

This holistic approach enables the exploration of various connected aspects and addresses specific unknowns within a broader, systematic series of tests on different typologies. These typologies, while sharing similar characteristics, vary in parameters (Fig. 1). This method allows for a comprehensive understanding of the materials and systems involved in construction. Starting from a general discussion on the importance of full-scale models and holistic approaches, it gradually shifts to how these methodologies are applied in the specific context of designing components like the LS. This section emphasizes the integration of ecological performance and adaptability in the detailed design of such components.

An example of this approach in action is an intensive workshop experiment focused on green facades as a passive energy-saving solution, particularly in the Mediterranean climate. The experiment involved testing green façades and green drapes, chosen for their simplicity in assembly and disassembly, ease of integration into existing buildings, and low maintenance requirements.

This approach also encompasses planning and managing natural areas and corridors on multiple scales, from individual materials to entire components. This multi-scalar planning supports a healthy ecosystem, integrating natural elements effectively within the built environment.

4.1 Physical performance in Mediterranean area

Environmental performance has been evaluated using an experimental workflow that employs Ladybug Tools for simulating outdoor temperature and comfort in courtyards, ideal for early-stage building design. These simulations are compared with both monitored and simulated data from ENVI-met. Notably, the simulated Universal Thermal Climate Index values show up to a 10 °C difference between ENVI-met and Ladybug Tools. This discrepancy underscores significant advancements in designing Liminal Space components for net-zero energy buildings [10].

In the model, the building is placed in a hypothetical scenario devoid of surrounding structures, considering the vertical XZ plane. This absence affects calculations, as surrounding structures typically act as shadow elements. The resulting model, as depicted in Figure 2, emerges after incorporating all these data. Additionally, it's crucial to consider the shape-related factors influencing their behavior.

4.2 Circularity aspects

In this segment of the study, the focus is on detailing the UpCycling design of vertical greening within the broader framework of green technology and sustainable practices. The study begins by addressing the concept of UpCycling in the context of vertical greening, viewing it as an integral part of a green technology strategy. This part of the discussion is broad, touching on the interrelationships of such designs across different organizations and the responsible management of material value chains.

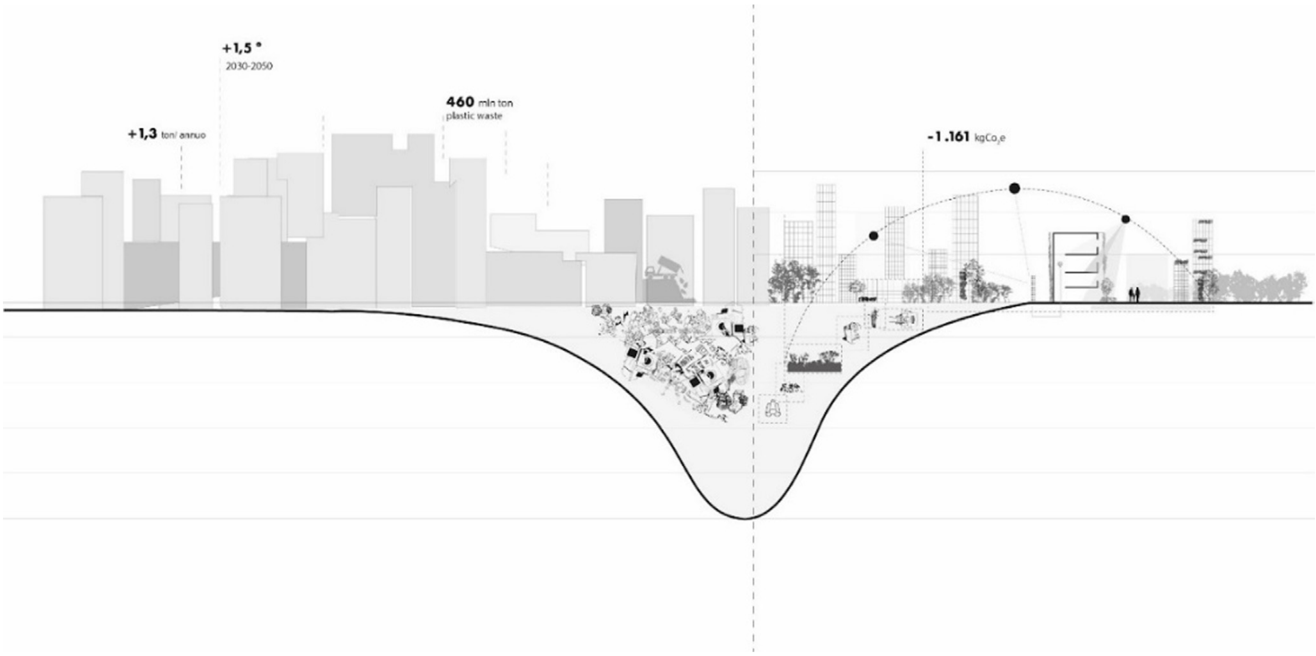

Fig. 1. Concept graph of the emission rate based on the life cycle of the optimized components (source: Parametric Results Experimentation in Green Responsive System workshop, ABITAlab Thesis, E. Catalano, F. Filice, 2022).

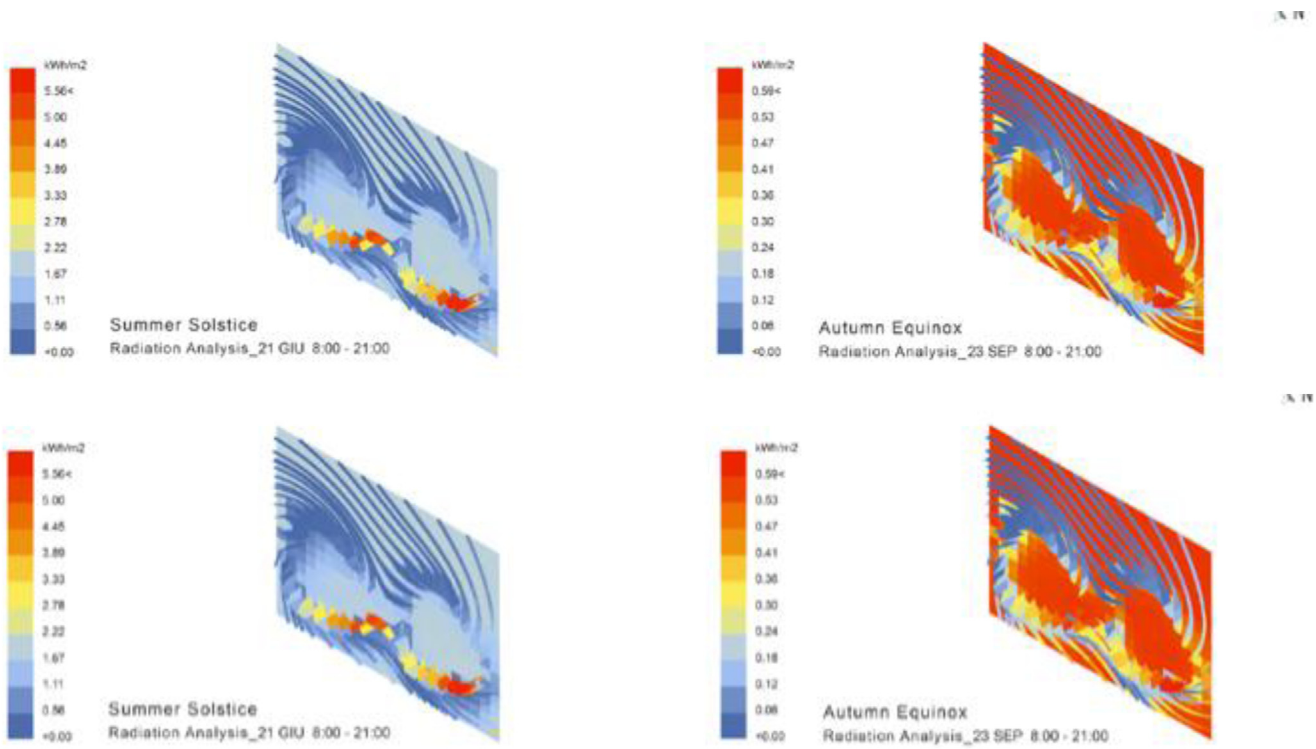

Fig. 2. Analysis results for the environmental performance analysis based on the optimized radiation of the components (source: Green Responsive System Workshop Experimentation, ABITAlab thesis work, D. Laganà, V. Cordì, 2022).

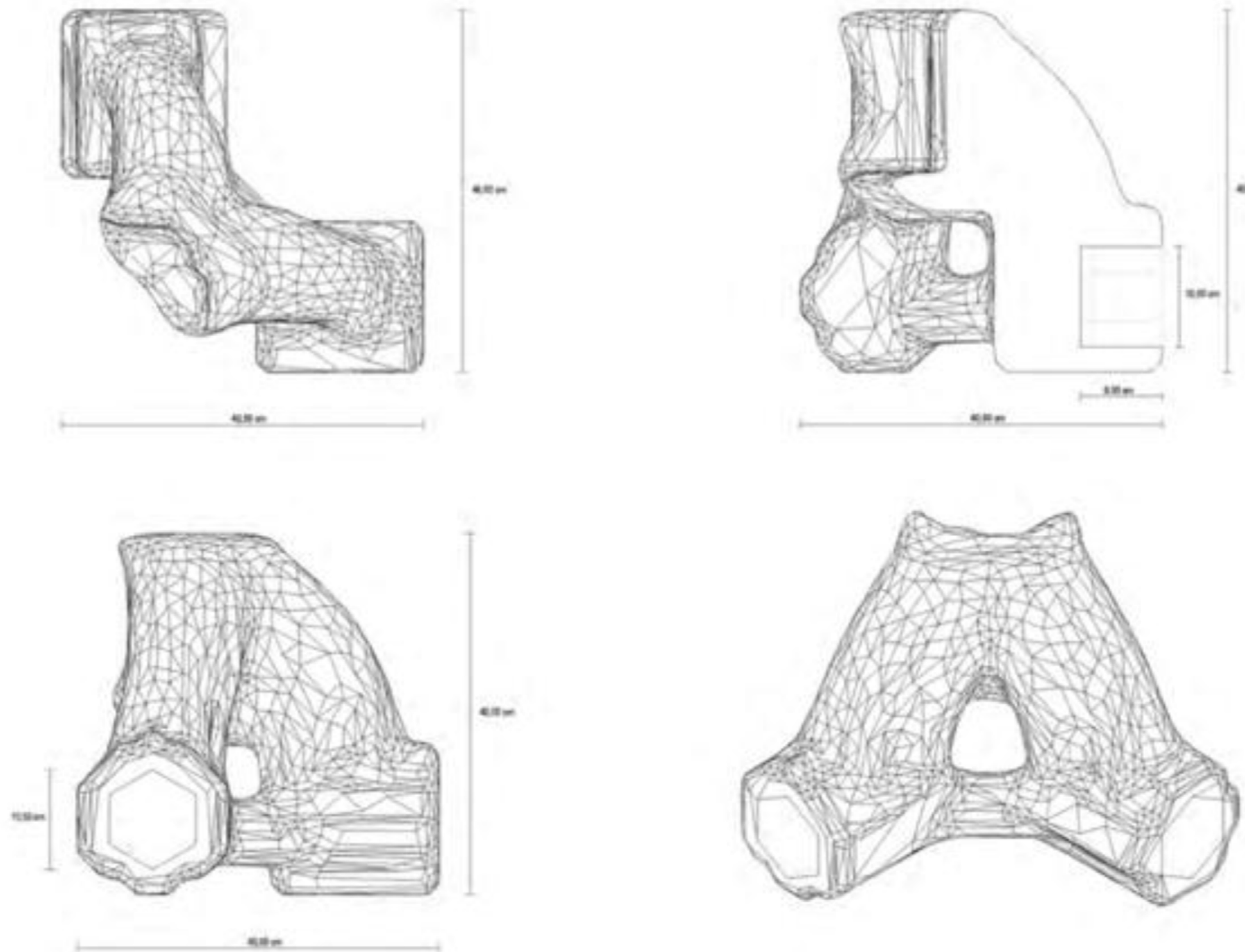

Fig. 3. The Parametric Design model of the node for the Greening module, as designed by the student team in the "additive manufacturing 4 prototyping" course, showcases a groundbreaking approach in the realm of architectural and technological component fabrication. This innovative project is made by Eliana Catalano, Federico Filice, Lucia Foti, Daniela Laganà, Francesco Notaro, and Angelo Modaffari from ABITAlab in 2022, exemplifies the fusion of parametric design tools with 3D printing technology.

As the discussion progresses, it becomes more specific. The study emphasizes the importance of maximizing the benefits of such designs over the entire lifecycle of a building. This is where the concept of the Circular Economy (CE) is introduced, broadening the scope to include not just the overall structure but also the specific flow of various building materials and component groups.

The Parametric Design model for the Greening module, as developed by the student team in the "Additive Manufacturing 4 Prototyping, represents an innovative intersection of ADC methodology and cutting-edge manufacturing technologies. This model exemplifies how parametric design tools, 3D printing, and Arduino technologies can be synergistically utilized to fabricate prototypes of technologically advanced components. [11] (Figs. 3 and 4).

The narrative then narrows down further to focus specifically on the Green Responsive Systems and their environmental design. This is where the Liminal Space (LS) comes into play as a specific component of interest. The study dives into the analysis of the materials and design aspects that constitute these systems, highlighting their role in climate change mitigation and in contributing to the circular economy within the construction sector. This transition from the general concepts of UpCycling and CE strategies to the detailed examination of the LS illustrates the process of applying broad sustainable design methods to the design of a specific, crucial component like the Liminal Space.

This study conducts an analysis of the circular performance of architectural components by monitoring their lifecycle assessment (LCA) using the Bombyx 2.0 Tool. This tool reports on embodied energy and the lifecycle of components. CO_2 emissions are defined as carbon dioxide emissions released during the manufacturing process of a material. In construction and architecture, CO_2 emissions encompass all emissions from the manufacturing process of materials, quantitatively expressed in $kg\,CO_2/m^2$ [12]. The study you're referring to, involving the analysis of the circular performance of architectural components using the Bombyx 2.0 Tool and detailed in the "Parametric Results Experimentation in

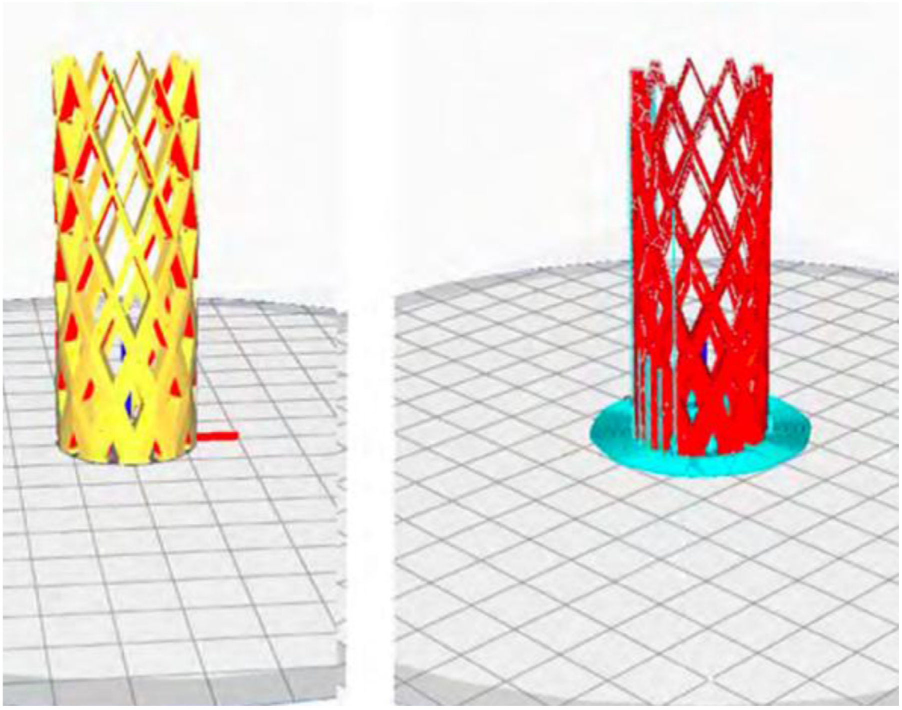

Fig. 4. Slicing and protypee definition of the Greening module designed by the student team in the additive manufacturing 4 prototyping. Stampa 3D e tecnologie arduino per la fabbricazione di prototipi di componenti tecnologici progettati con tools parametrici (source: Parametric Design Experimentation, Eliana Catalano, Federico Filice, Lucia Foti Daniela Laganà, Francesco Notaro, Angelo Modaffari, ABITAlab, 2022).

Green Responsive System workshop" by E. Catalano, F. Filice, and others, focuses on monitoring the lifecycle assessment (LCA) of these components. To understand how the values in Figure 5 are obtained, it's essential to look at the key aspects of the LCA process, the role of the Bombyx 2.0 Tool, and the specific parameters considered in the study. Initially, data about the materials, manufacturing processes, and transportation methods are collected. The Bombyx 2.0 Tool analyzes this data to calculate the embodied energy and CO_2 emissions. It quantifies CO_2 emissions in terms of $kgCO_2/m^2$ [12], providing a standardized metric to compare different materials or components. The values in Figure 5 of the study are obtained through a comprehensive LCA using the Bombyx 2.0 Tool, which considers various factors such as embodied energy, CO_2 emissions, and the inclusion of recycled materials. The analysis is framed within specific boundary conditions that encompass the entire lifecycle of the architectural components, from raw material extraction to end-of-life scenarios. By analyzing these factors, the study aims to optimize the circular performance of architectural components, thereby reducing their environmental impact.

5 Results

An experimental investigation at the building scale was conducted to study the environmental aspects in the early design phase that incorporate circular and ecological materials. The biological interactions between the built and the natural environment is enhanced with the upcycling design of the "Liminal Space" (LS) through the proto-typological model for the "Green Responsive System" (GRS). To achieve this, we try to experiment and visualize factors that optimize climatic adaptation, circularity, and biodiversity in the built environment. Therefore, we believe that research in architecture, in particular, should be open and adaptable. Additionally, architectural demonstrators, pavilions, and physical experiments are the principal subject of proto-typological design. A need for prototyping is emerging in the innovation of design processes toward applying emerging technologies, where the prototype is viewed as an integral step in the advanced processes of determining technological maturity (TRL). A trl evaluation process is used to assess the technological maturity of tested construction technologies, identify new supply chains for the upcycling of constructive components, and formulate new hypotheses based on the environmental parametric analysis of the context study. Controlling the flow of information, directly related to the material and immaterial resources of significance for innovation (radical innovation) by using "open data" and digital instruments (additive manufacturing). While defining their purpose, these full-scale applications must be defined within the overall research objective: how to integrate computational approaches into a workflow of living architecture design; how to teach data-native students both the use of digital tools for design and environmental design thinking for creating sustainable architecture. A workshop studio was organized to design and prototype a Green Responsive System in response to these two questions. A computational

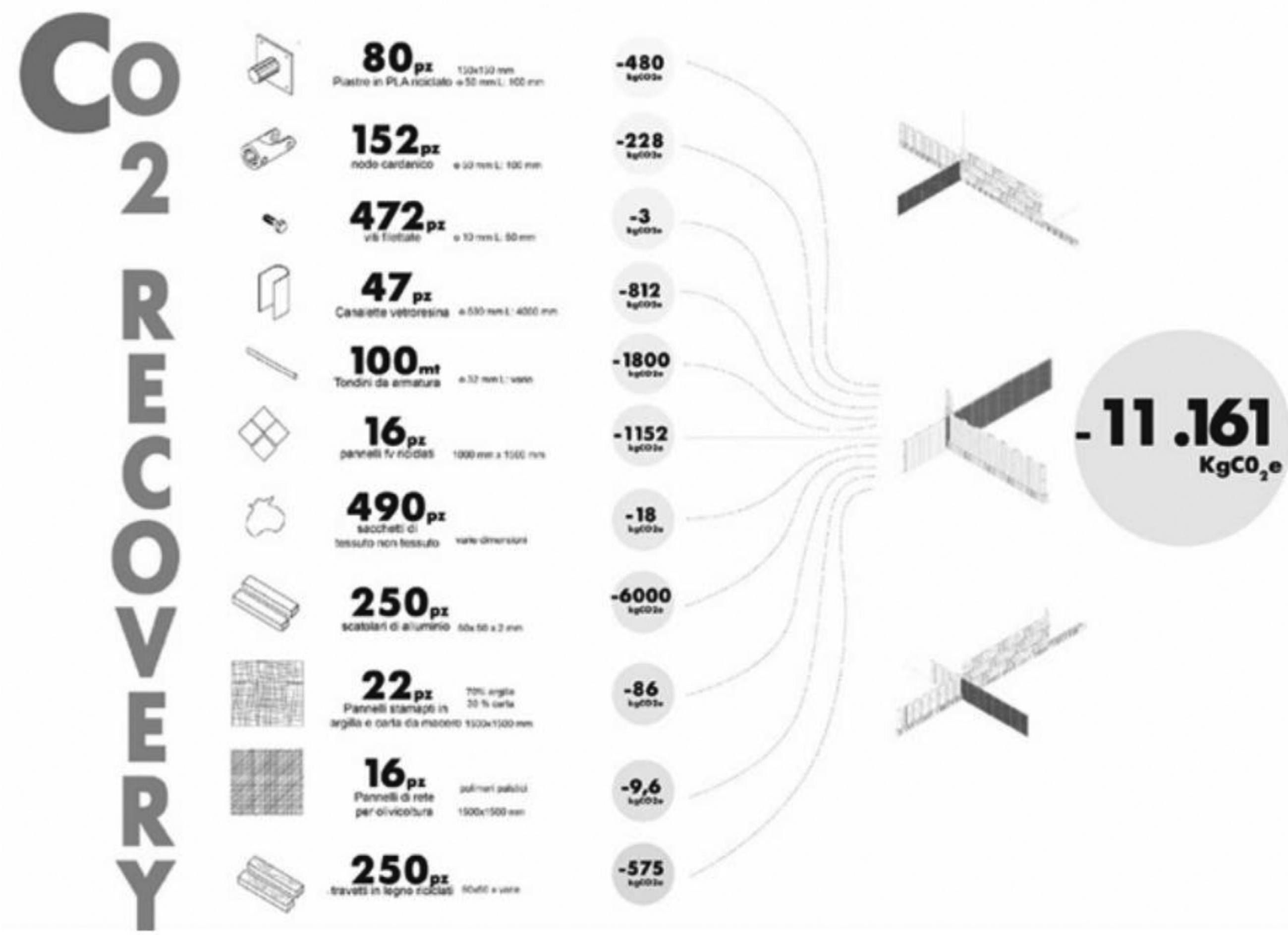

Fig. 5. Emission rate definition based on the life cycle of the optimized components for the UpCycling of a Prototypological Liminal Space (source: Parametric Results Experimentation in Green Responsive System workshop, ABITAlab Thesis, E. Catalano, F. Filice, 2022).

workflow (Fig. 6) was explored during the design phase, including environmental optimization and the production of parametric geometry.

The use of tools like Galapagos in Grasshopper represents a significant advancement in architectural design. Galapagos is an evolutionary solver plugin for Grasshopper, a visual programming language integrated with Rhino 3D. It employs evolutionary algorithms to solve complex optimization problems in design. The optimization algorithms in Galapagos can be used to minimize material usage without compromising structural integrity. 3D printing translates these optimizations into physical models, ensuring that the material is used efficiently, which is crucial in sustainable design practices. Fabrication of the complex Green Responsive Systems was based on the digital model created during the design phase (Fig. 7). By the end of this workshop, an "open knowledge platform" will be built, capable of transferring and exchanging information and experiences. The advancement of such a platform yields measurable results, albeit through the complexity of its own language, tracing its readability within its narrative spaces. As a result, the research experiences will be transferred to the teaching experiences.

In this part of the paper, the focus shifts from a general sustainable design methodology to the specific design of the Liminal Space, a critical component in urban environments. The paper starts by reviewing proto-typological methods, which represent an innovative approach in designing systems and components that are adaptive to the built environment and effective in mitigating climate change effects, particularly in urban Mediterranean areas.

The narrative then illustrates this approach through practical examples and experiences. It demonstrates how the design of urban outdoor spaces, following these proto-typological methods, can enhance comfort both indoors and outdoors, thereby contributing to energy savings in individual buildings. This enhancement is achieved by creating microclimates and increasing ecological value, employing circular model practices in life cycle management - a concept known as cradle to cradle.

As the discussion progresses, the paper delves into the interplay between buildings and urban microclimates, illustrating how this relationship is crucial in the overall sustainable design process. It highlights how urban microclimates significantly affect a building's energy consumption and indoor climate, and how buildings, in

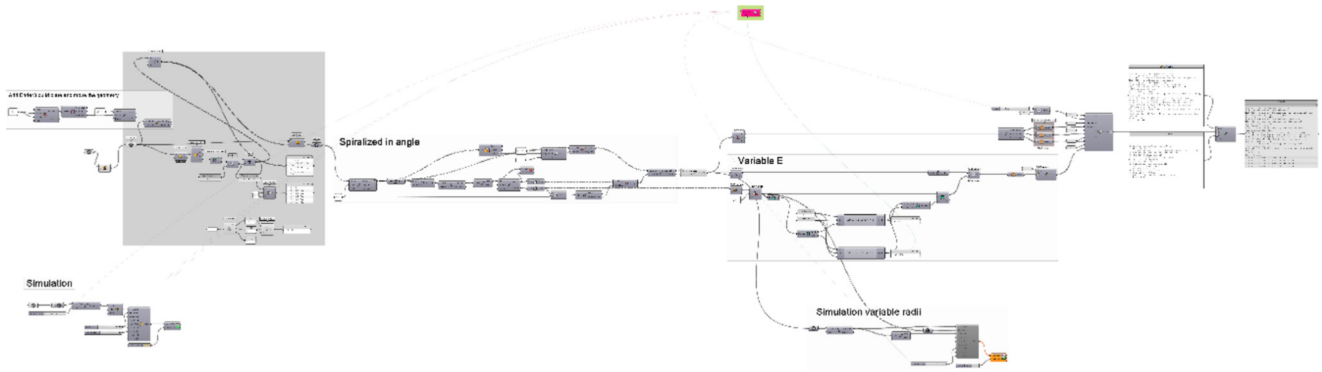

Fig. 6. Grasshopper definition based on the parametric UpCycling of the Proto-typological Liminal Space (source: Parametric Results Experimentation in Green Responsive System workshop, ABITAlab Thesis, E. Catalano, F. Filice, 2022).

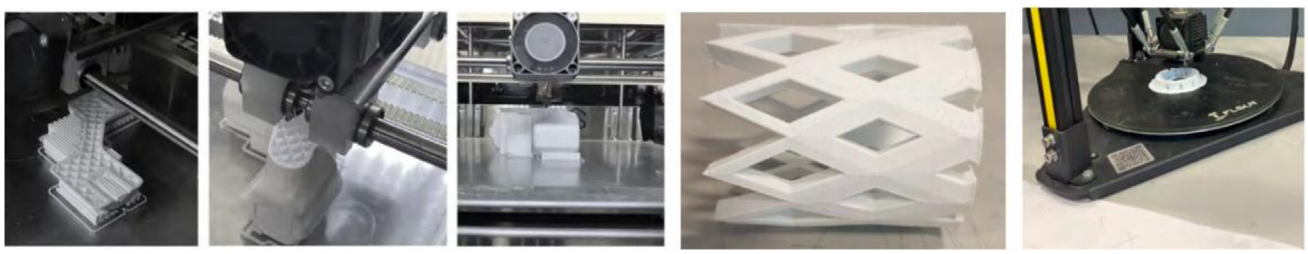

Fig. 7. Prototyping phases of the Greening module designed by the student team in the additive manufacturing 4 prototyping. Stampa 3D e tecnologie arduino per la fabbricazione di prototipi di componenti tecnologici progettati con tools parametrici (source: Parametric Design Experimentation, Eliana Catalano, Federico Filice, Lucia Foti Daniela Laganà, Francesco Notaro, Angelo Modaffari, ABITAlab, 2022).

turn, impact these microclimates. This interconnection underscores the importance of considering urban microclimates in building design.

Finally, the paper narrows down to the specific design of the Liminal Space. It connects the broader principles of sustainable design and the influence of urban microclimates to the design of this specific component. The Liminal Space is presented as a solution that embodies the principles of proto-typological design and circular economy, tailored to enhance the ecological and energy performance of buildings in urban settings. This part of the paper demonstrates how the general methodology of sustainable design is applied to the detailed design of a vital component like the Liminal Space, contributing to the overall sustainability and efficiency of urban environments.

6 Conclusions

In the conclusion of the paper, the process from a general sustainable design methodology to the specific design of the Liminal Space is synthesized and reiterated. Initially, the paper emphasizes the importance of using digital tools like plug-ins and workflows in sustainable architectural design. These tools are instrumental in mitigating climate effects on the built environment and optimizing design processes to minimize Global Warming Potential, particularly during the production stage.

From this broad focus on digital tools and methodologies, the discussion then converges into the formulation of five distinct paradigms. These paradigms, derived from the general sustainable design approach, are tailored to cater to different aspects of sustainable and regenerative design. They serve as adaptable methodologies that can be applied to various cases, including the design of specific components like the Liminal Space.

As the conclusion progresses, it highlights how these methodologies, while broad in scope, provide a clear scientific positioning for addressing specific challenges in sustainable design. The design of the Liminal Space is presented as an embodiment of these principles, showcasing how the paper's broad sustainable design methods are applied to create a specific, innovative component that contributes to sustainability in the built environment.

Thus, the conclusion ties together the journey of the paper from general methodologies in sustainable design to their application in the detailed design of the Liminal Space, underscoring the role of these methods as drivers of innovation and sustainability in the field of architecture and construction. This approach acknowledges the evolving nature of sustainable design, where methodologies adapt and evolve to meet new challenges and opportunities, particularly in the design of critical components like the Liminal Space.

7 Implications and influences

The framework presented in this paper aims to show how the UpCycling of the LS strives to achieve a high-quality system. The computational approach employed underscores the "positive factor" in any LS configuration, highlighting the effectiveness of this methodology.

In summary, this investigation represents an initial effort to integrate design and production tools within a parametric environment. It spans from "regenerative-design" for climate neutrality to the use of additive manufacturing. This integration facilitates the development of an automated robotic system for 3D printing, enhancing efficiency and effectiveness. Such a system holds potential for broader application and implementation, including the exploration of new extrusion materials for prototypes and construction in the building industry. This approach not only advances the field in terms of technological innovation but also contributes to sustainable and climate-resilient construction practices.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Data availability statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Author contribution statement

Consuelo Nava: Conceived the research theme A proposal for frontier research: UpCycling Liminal Space" and supervised the Ph.D. student's research activities. Contributed to the writing of the conclusion alongside **Domenico Lucanto.** Domenico Lucanto: Conducted the primary research activities and experiments as part of his doctoral research titled "Circular Processes and Enabling Technologies for the UpCycling of innovative frontier systems. Advanced Circular Design for the Green Responsive System prototype." Responsible for drafting the initial sections (par.1,2,3,4) of the paper and contributed to the writing of the conclusion.

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