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CIRCULAR DESIGN STRATEGIES THROUGH ADDITIVE MANUFACTURING: *MODOM*, A "CIRCULAR BUILDING" HOUSING MODEL

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Abstract. The doubling of the global use of raw materials in the last century is an established environmental emergency due to an all too common "take – make – dispose" linear development model. Strategic plans within the Green Deal, such as the Circular Economy Action Plan, highlight the key role of building design as an enabling driver for process cyclicality. Against this backdrop, the paper describes the results of an experimental research project aimed at the technological design of a "circular" housing model. The integration of circular economy principles into the design process was pursued through the technology transfer of Additive Manufacturing principles as an enabling technology of Industry 4.0. The research is based on the first phase of critical analysis of two types of case studies: one referring to Circular Buildings, the other referring to 3D printed buildings, through a common reading method based on "circular" indicators extrapolated from the current literature. The evaluation of the results obtained determined the prerequisites for designing a replicable Circular Building model by 3D printing using a lignin-based biopolymer. The adoption and combination of these seemingly opposing themes was a key strength and asset to the project in terms of benefits such as energy savings, lead time, and cost savings at all life cycle stages.

Keywords: Additive manufacturing, circular building, bio-composite.

1. Introduction

The doubling of the global use of raw materials in the last century is now an acknowledged environmental emergency due to a linear "take – make – dispose" development model that is still too widespread [1]. Strategic plans within the Green Deal, such as the Circular Economy Action Plan, highlight the key role of building design as an enabling driver for process cyclicality. Several factors, including the consequences of the construction sector's responsibility for CO_2 emissions, have prompted the European community to propose a number of resolution strategies through guidelines and directives, such as Agenda 2030 and the Paris Agreement, to raise awareness of sustainable development.

In line with the goals set by SystemiQ and the Ellen MacArthur Foundation [2], including the Design and Production of Circular Buildings and the Closing of Construction Cycles, there is an urgent need to address the total impact of emissions, resource consumption and waste generation in the construction sector. In this sense, the strategies of the Circular Economy and the Action Plan focus on responsible design as a key tool for the optimal use of resources [3]. The change of course towards circular processes is implemented by taking the linear model and changing the final step of waste into a resource, thinking in phases of reuse/recycling of products, components, elements and materials [4]. Emphasising the relationship between the Circular Economy and sustainability concepts, the influence of digital technologies through Industry 4.0 and life cycle assessment breaks through [5].

The transition to a Circular Economy model can be driven by the process of industrial digitisation that enhances the connection of products and factories to achieve a more sustainable production cycle, both economically and environmentally. These principles are translated thanks to the unbreakable link between the dictates coming from the Circular Economy and the innovations coming from the technological era in which we find ourselves. The current historical context is influenced by innovations from the fourth industrial revolution, focusing on digitalisation/automation processes.

The relationship between the Circular Economy and KETs undoubtedly also involves the construction sector, posing a significant challenge for the latter's future, given its considerable impact on the environment [6]. The link with the Circular Economy can be made according to specific common goals, such as reducing waste, rethinking production chain processes and using technologies derived from Industry 4.0 such as IoT, Big Data, 3D printing, Additive Manufacturing techniques etc.

Broadly speaking, Additive Manufacturing is "a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" [7]. In design, architect Frank Duffy first proposed the concept of building "in layers" in the 1970s. Stuart Brand developed the concept in the 1990s, and today it is more widely known, though not yet a widely adopted method, for carrying out a circular-compliant building design [8]. Brand's model considers the building to be made up of six separate and interconnected layers, each with its characteristics and life span: site, structure, skin, services, space and things [9]. In this sense, the layer-by-layer fabrication capability of 3D printing translates Stuart Brandt's concept well. It presents unique advantages in the circular construction approach, such as rationalisation of connections, reduced construction time, efficient use of energy, and reduction of production waste.

The relationship between Circular Economy and Additive Manufacturing is emerging as a new systemic logic to define new opportunities for circular sustainability.

In this scenario, the paper presents the results of experimental university research whose objective concerns the technological design of a "circular" housing model, applying the principles of Additive Manufacturing and relating them to the concept of Circular Building. Starting from the results of the systematic work of retrieval, classification and interpretation of the themes and case studies, the design of a housing micro-architecture to be 3D printed through the use of bio-based material, a lignin-based biopolymer, was initiated. In response to the increasingly common need for temporary solutions that incorporate the possibility of being assembled/disassembled easily and in a short time. The research became a moment to reflect on the social, cultural and environmental effects of designing, building and managing sustainable technological solutions through an innovative concept of Low-Cost housing with expandable units or with local materials. Finally, the research became an opportunity to reflect in applicative terms on the Low-Cost approach in a broader vision, considering the entire life cycle of buildings and focusing on the Circular Economy theme pursued through Additive Manufacturing.

2. The scientific context: Circular economy enabled by additive manufacturing

From the scenario of profound environmental emergency described above, the need for a transition to a circular model is driven to a large extent by the lack of finding resources [10], so it becomes necessary to start thinking about processes whose aim is to reuse/reduce and finally recycle elements, products and materials already placed in the production cycle. This means that all resources extracted from the ecosystem must be exploited within no-waste processes, avoiding the removal of additional assets, thus maximising reuse practices at all scales.

A definition of a circular building is provided in the report "A Framework for Circular Buildings: Indicators for possible inclusion in BREEAM" [11] – in line with the Transition Agenda for Circular Buildings in the Netherlands. Thus, a Circular Building is defined as "a building that is developed, used and reused without unnecessary depletion of resources, [...]. It is constructed in an economically responsible way and contributes to the well-being of people and the biosphere [...]. The technical elements can be dismantled and reused, [...]". For these purposes, Brandt's conceptual model mentioned above can provide designers with a useful means of shaping their decisions to conform to circularity. A package of specific requirements can be associated with the function that each appropriately defined layer performs within the building. This allows a very effective selection of the characteristics of the constituent materials, focusing exclusively on their relevant purposes [12].

By identifying the different layers, very specific strategies can be adopted for each of them. This helps a lot in eliminating redundancy both in the design of the building and in the production material. In addition, building elements with more specific characteristics increase their residual value, making their reuse opportunities easier to determine and recycling cheaper to perform. Building in layers leads to focusing on each element and its specific characteristics when conceiving and designing a building, thus shaping the assembly components separately – making them easier to remove individually, even at different times, depending on their different lifespans. Finally, layered construction has implications with respect to reducing production costs [13]. In this sense, Additive Manufacturing processes have the characteristics to support Circular Economy initiatives. Additive Manufacturing reduces the waste generated during production and saves input materials [14].

Furthermore, it supports reuse and recycling processes by using recycled materials as inputs for the production process. Additive Manufacturing also encourages repair and refurbishment processes and extends the product life cycle by printing on-site the necessary parts for broken/unfunctional products. This transition reconfigures the supply chain to achieve the ideal of a circular economy together with improved resource efficiency [15]. Ultimately, the concept of layering, transferred to the field of Additive Manufacturing, can be further synthesised and made "circular" by the monomatericity of the layers that make up the 3D printed construction solution. Advances in materials science and technology offer designers a wide range of more sustainable materials for a multitude of applications. Material innovations with respect to 3D printing extrusion processes are moving towards supporting the use of biomaterials for production, which, through the printing methodology, are able to play both structural and non-structural roles.

Interest in using biomaterials for 3D printing is ex-

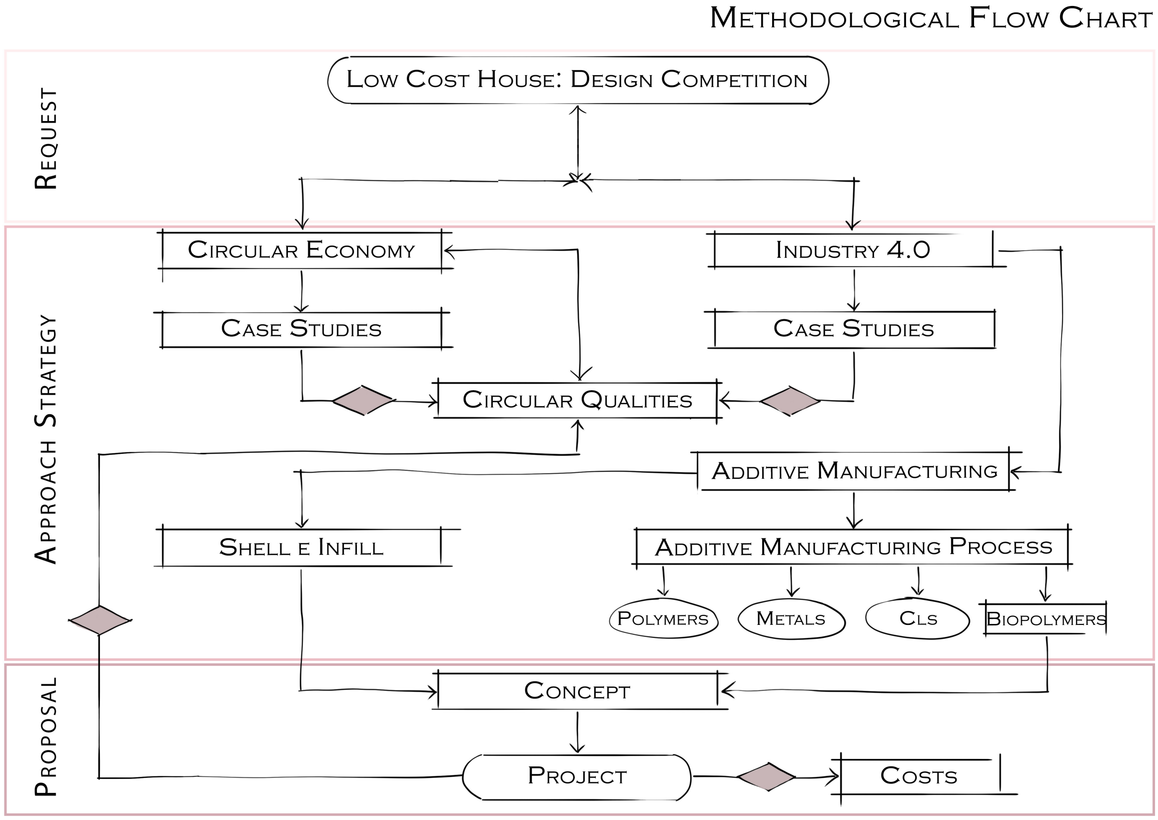

Figure 1. Methodological Flow-Chart.

panding as several studies have explored that the use of biomaterials requires less material usage and with zero waste, further increasing the environmental benefit [16]. The focus on the design and production of 3D-printed Circular Buildings using bio-based materials, therefore, provides an interesting scenario for the sustainable production and recycling or recycling of waste materials such as wood flour, rice husks or miscanthus fibre etc. The decomposition process of the biocomposite can be understood as the reverse of the production process, just as with cultivated wood, and can also be disposed of by burning without producing additional CO_2.

The latter is in line with the Ellen Mac Arthur Foundation's definition of circularity, as the preservation of the value of buildings and their components is guaranteed by optimising the cycles of use and reuse with minimum use of virgin resources. Furthermore, the importance of both technical and biological cycles is emphasised [11]. According to the biological metaphor, they "melt without a trace", as what disappears reappears embodied in a new element without any waste throughout this process. In this scenario, the goal coming from the Circular Economy of initiating intelligent production based on the reduction of resource consumption and waste production through the optimisation of industrial processes is translated.

3. The MoDom, a "Circular Building" Housing Model

The research was developed by adopting a deductive schematic scalar methodological procedure, moving from the definitions of the characteristics/qualities that identify a circular building to the construction of the variables that can be implemented through 3D printing processes. In this phase, a theoretical reference model was developed for the purposes of Low-Cost temporary housing solutions.

Specifically, the study is structured in three phases:

(i) the adoption of Research Criteria through Circular Qualities Application and case studies;

(ii) the experimentation;

(iii) the evaluation of the potential impact of Circular Building on cost scenarios (Figure 1).

3.1. A Research Criteria: Circular Qualities Application and case studies

In the first instance, the research aimed to identify the relationships between Circular Economic and Industry 4.0 enabling technologies within the construction sector, as described in the paragraph "Circular Economy enabled by Additive Manufacturing". The need to implement criteria and indicators to assess the circular potential of technical options on the one hand, and their efficiency on the other, to optimise resource use and reduce waste was highlighted. The different declinations of circular design have been analysed about design strategies, theories, approaches and principles that may respond to those of the circular economy, even if not directly derived from them. Starting with experiments strongly related to Circular Design and moving on to experiments from Additive Manufacturing, the research identified some case studies, subsequently analysed using common reading indicators, deduced from the current literature in the sector, the *Circular Design Qualities*[1]. Computerised sheets have been defined against sixteen circularity criteria. On the one hand, these aim to measure the circularity of a building product, and on the other hand, to demonstrate the added value in the revision framework from the beginning of the design process to the decommissioning phase. These criteria are recurrent when strongly related to *Design for Reuse*, *Design for Longevity* and *Design for Disassembly.*

Ultimately, any building project that meets these requirements can be defined as Circular. In a perspective that aims to outline the experiences and principles related to sustainable building concepts, it is necessary to critically describe, through some of the Circular Design Qualities prepared by VUB, the experimentation of the first prototype of "Circular Building", carried out by Arup Associates, during the London Design Festival in 2016. The experimentation aims to test the maturity of Circular Economic thinking within the construction industry. The Circular Building was constructed using rented rather than purchased materials and products. Every part of the building can be removed with minimal damage, reused, regenerated or recycled at the end of its life. The use of mechanical and pressure connections is in line with the construction solutions adopted, allowing it to meet the criteria of "independent" and "reversible" and thus facilitating the deconstruction process. In this sense "Circular Building" becomes a promoter of and responds to indispensable qualities for a circular model, such as the possibility of being easily disassembled, thanks to the non-use of resins and the use of so-called reversible elements. The evaluation criteria highlighted how the variables chosen in the design are closely related to determining the levels of circularity, such as the proportion of materials used, reversibility strategies and the circularity of resources.

Within the category of purely "circular" experiments is the example of the "People's Pavilion" designed by the Bureau SLA and Overtreders W team using 100 % materials borrowed from traditional suppliers, manufacturers, and local inhabitants. The temporary use of the pavilion meant that the disassembled elements were returned intact to the suppliers, providing for a future phase of assembly/use of the parts and designing, ex-ante, the "reused" criterion. This last phase is in line with the Ellen Mac Arthur Foundation's definition of circularity, as the preservation of the value of buildings and their components is guaranteed by optimising the cycles of use and reuse with minimum use of virgin resources [17].

The "U Build – Box House" project was analysed to conclude the cycle of circular experiments. The system is based exclusively on a flat-pack kit made up of wooden parts and stems from Studio Bark's desire to make construction "truly accessible" to the public. The components can be quickly fitted together to assemble the structure of a building and easily disassembled, recycled or reused at the end of the building's life. A further feature of the project is producing the box with local materials while also paying attention to the principle of resourcing [18]. In this first systemic tranche, the methodology of reading has shown how Circular Buildings respond to the circular indicators "reversible" and "durable". Concepts that are widely addressed in all Circular Design strategies. The Circular Design Qualities have been applied as reading indicators to experiments coming from Additive Manufacturing.

This method of reading aims to show that even a project realised with construction strategies different from the traditional ones, such as those coming from Additive Manufacturing, can be read through Circularity indicators, underlining the link between Circular Economy and 3D Printing. Specifically, the following experiments were analysed: "Office the Future", "Urban Cabin", ""PassiveDom", and finally "Amie". This paragraph aims not to describe the design choices but rather to offer a critical analysis of the projects mentioned, focusing on the circular qualities that can be found in projects from Additive Manufacturing. Suppose in the case of Circular Buildings, the recurring Circular Design Qualities lie in the "reversible" and "durable" of the material resources used, in the case of 3D printed buildings, the systematic quality is "100 % pure", thanks to the monomatericity that distinguishes the experiments. Another fundamental requirement for Additive Manufacturing construction strategies is to minimise the number of connecting elements, which are sometimes moulded and made dry-assemblable, thus reducing construction waste. The analysis of the case studies concerning qualitative indicators and the study of research topics related to the principles of the Circular Economy and innovations from Industry 4.0 led to a design reflection. "Reversible", "durable", and "100 % pure" requirements were identified as key indicators for a possible temporary housing solution.

[1]The BBSM research was conducted by VUB (Vrije Universiteit Brussel) Architectural Engineering and was financed by European Regional Development Fund (ERDF) and the Brussels-Capital Region. Project partners: UCLouvain, Rotor, Belgian Building Research Institute. Source: `https://www.vub.be/arch/page/circulardesign`. Although less relevant for our purposes, the additional Circular Design Qualities of the Belgian study identified are: Safe and Healthy, Durable, Manageable, Accessible, Independent, Compatible, Multi-purpose, Varied.

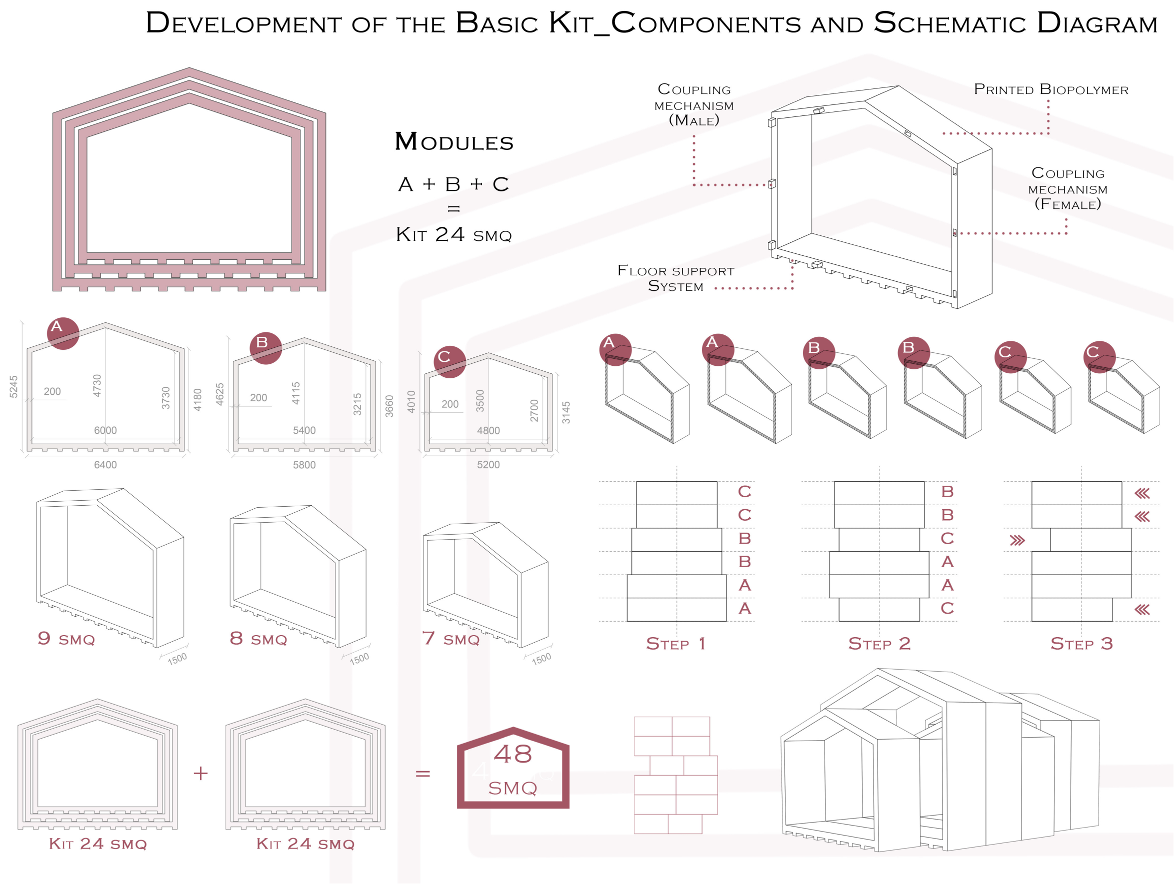

Figure 2. Composition diagram, MoDom circular housing model.

3.2. The experimentation

The experimentation is an opportunity for research activity, still in progress by the scientific heads of the study. The first results concern developing a housing system, a micro-architecture designed as an aggregable and temporary housing system. Starting from the archetypal home, MoDom is a 3D printed housing model using a lignin-based biopolymer whose properties are similar to those of wood, but whose workability can be likened to that of a 3D printable plastic material. Lignin is, in fact, a rigid timber component discarded in the pulp and paper production process. The process combines recovered lignin with natural fibres – such as flax, hemp or other fibre plants – to create a composite processed at high temperatures in the same way as synthetic thermoplastics. The Circular Building consists of 6 stackable modules in 2 transport kits with three types of dimensions. The width of each module is 1 500 mm, the height of which varies according to the kind of module A, B and C, 5 200, 4 600 and 4 000 mm, respectively (Figure 2). The composition-design scheme varies according to the functionality of each module. The kits will be prepared with a special module, including the off-grid systems for the toilet. For greater space flexibility, these kits can be enriched with two additional "extra" modules corresponding to two shaded loggias to filter the perception of inside outside (Figure 3).

MoDom is assembled without the use of connecting elements. In fact, during the printing phase, a male-female connection system is installed directly on the printed module. In addition, the technological solution chosen avoids the installation of foundations on which to erect the architecture. In fact, each module is provided with grooves in the lower part, which allows the module to be raised and prevents humidity from rising (Figure 4). Stuart Brand's "layer model" was translated through a careful stratigraphy, including the skin of the circular building to the cavity prepared for the systems (Figure 5). The printing methodology, based on Shell&Infill, allows to configure through a single material its technological-structural properties not only through the percentage of "Infill" filling of the material (0–100 %) but also through the type of "Pattern" filling that will be used (honeycomb, linear, triangular, grid, etc.) [19]. This makes it possible to define whether the moulded element can perform structural functions or act, for example, as a container for implants.

3.3. Potential Impact of Circular Building on cost scenarios

Adopting the design choices mentioned in the previous paragraph has highlighted a further key aspect of the experimentation regarding the impacts on the entire life cycle. We refer to the construction technologies

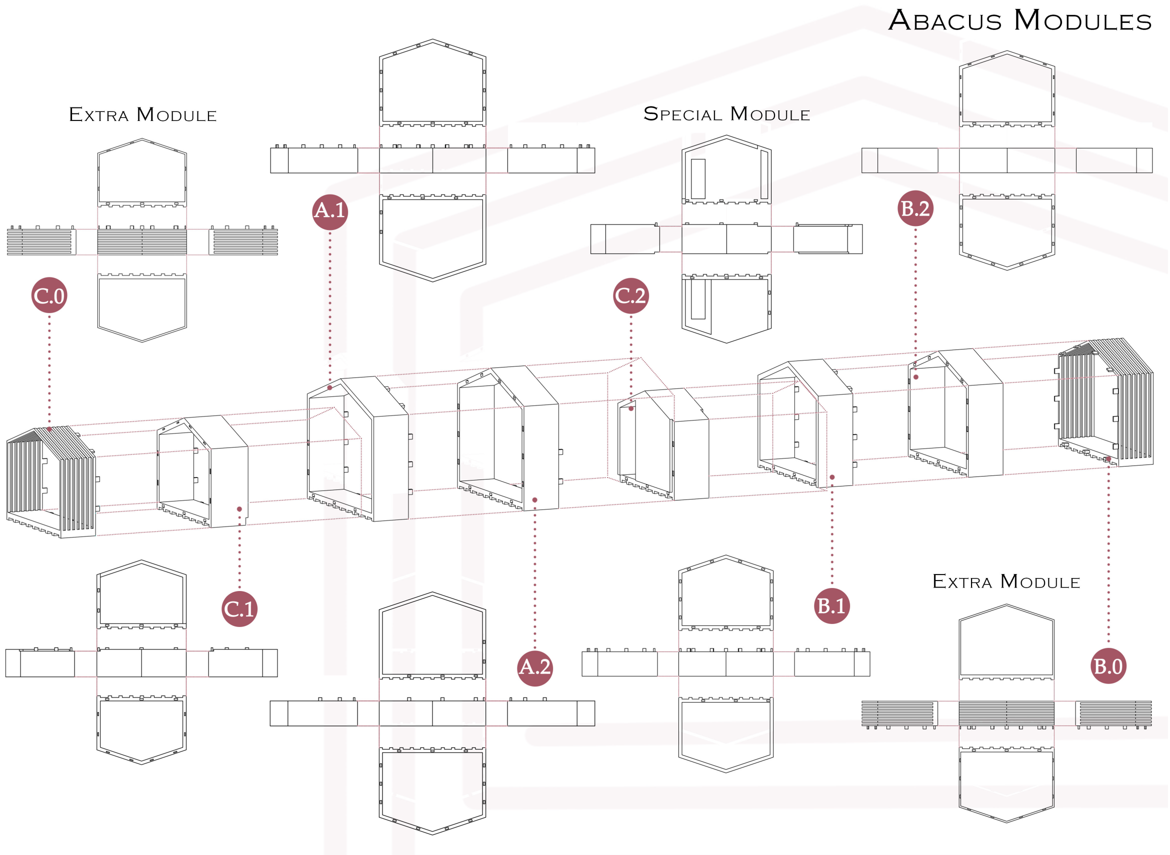

Figure 3. Axonometric projection of MoDom modules.

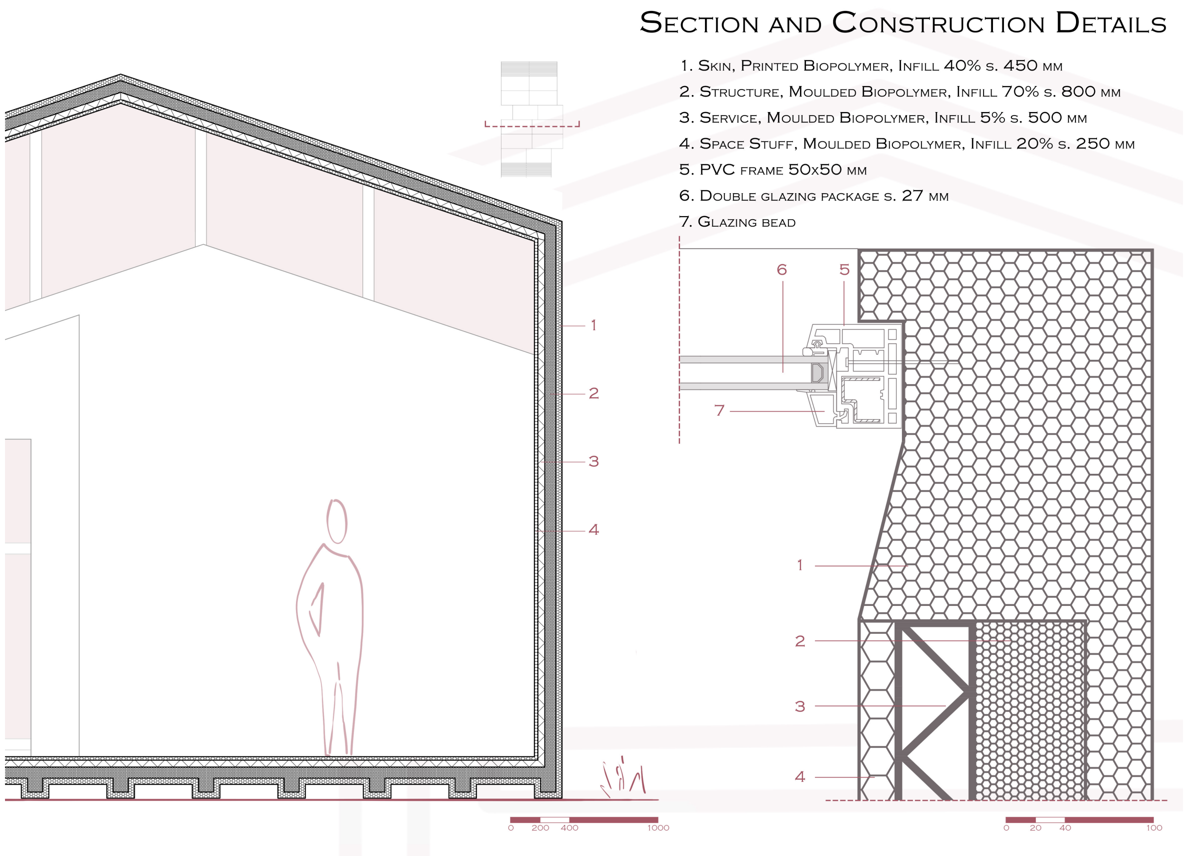

Figure 4. Cross-section and Detail of MoDom.

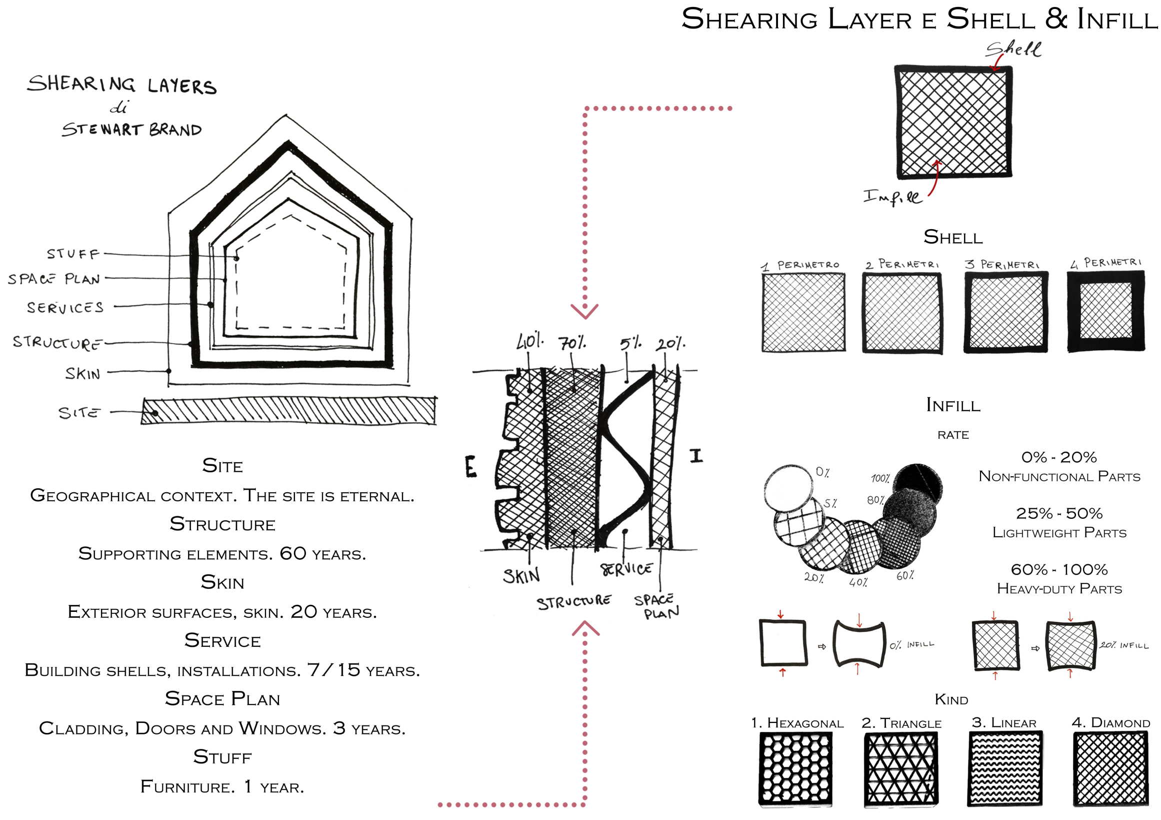

Figure 5. Stuart Brand's six-layer model applied to the 'Shell&Infill' principle of 3D printing.

through the adoption of 3D printing and concerning the modularity of the designed system.

According to a McKinsey report [20], modular construction can speed up construction projects by up to 50 % and potentially reduce project costs by 20 %. If in a first phase, the trial shows a high production cost, due to the machines that do the printing, and a longer design time, time and costs are halved compared to the cost items on "foundations", "off-site process" and "maintenance". MoDom does not require foundations, as the modules are designed to be lightweight for transport. The off-site production process is much faster than the equivalent on-site construction process. The moulded modules, including connection systems, will be installed on-site, allowing for ease of assembly and reducing assembly/disassembly time. In this sense, the potential of Additive Manufacturing significantly reduces the need for resources by exploiting the capabilities of materials that could not be obtained through conventional processes. In experimentation, the concepts of the flexibility of spaces and reversibility of the construction process substantiate the project as part of an ecosystem; their objective is to establish a Circular Economy process. Finally, the maintenance aspect has a significant impact on the percentage of costs that would be incurred in a conventional building. In the 3D printing process, the elements that need to be replaced or repaired are not already placed on the market but are themselves printed for the specific case. This means that parts and resources that would otherwise be taken from the ecosystem are not introduced into the production cycle.

4. Conclusion

The lines of research that revolve around the themes dealt with can represent a fertile field of experimentation of the knowledge of methodologies and operational tools necessary to develop models of housing innovation integrated by a different approach to the management of the project process. At the end of the experimentation, the project was subjected to the same evaluation of the Circularity used to read the case studies. This resulted in its validation through a feedback process, through the Circular Design Qualities (Figure 6).

More specifically, it should be noted that MoDom responds to the circular indicators of:

- "reversible", through the design of male-female connections without the use of adhesives or sealants, allowing this to be completely disassembled;
- "100 % pure", the entire structure is moulded through the lignin-based biopolymer with structural stiffness capabilities;
- "renewed", the choice of material has a significant influence on the circularity characterisation, the

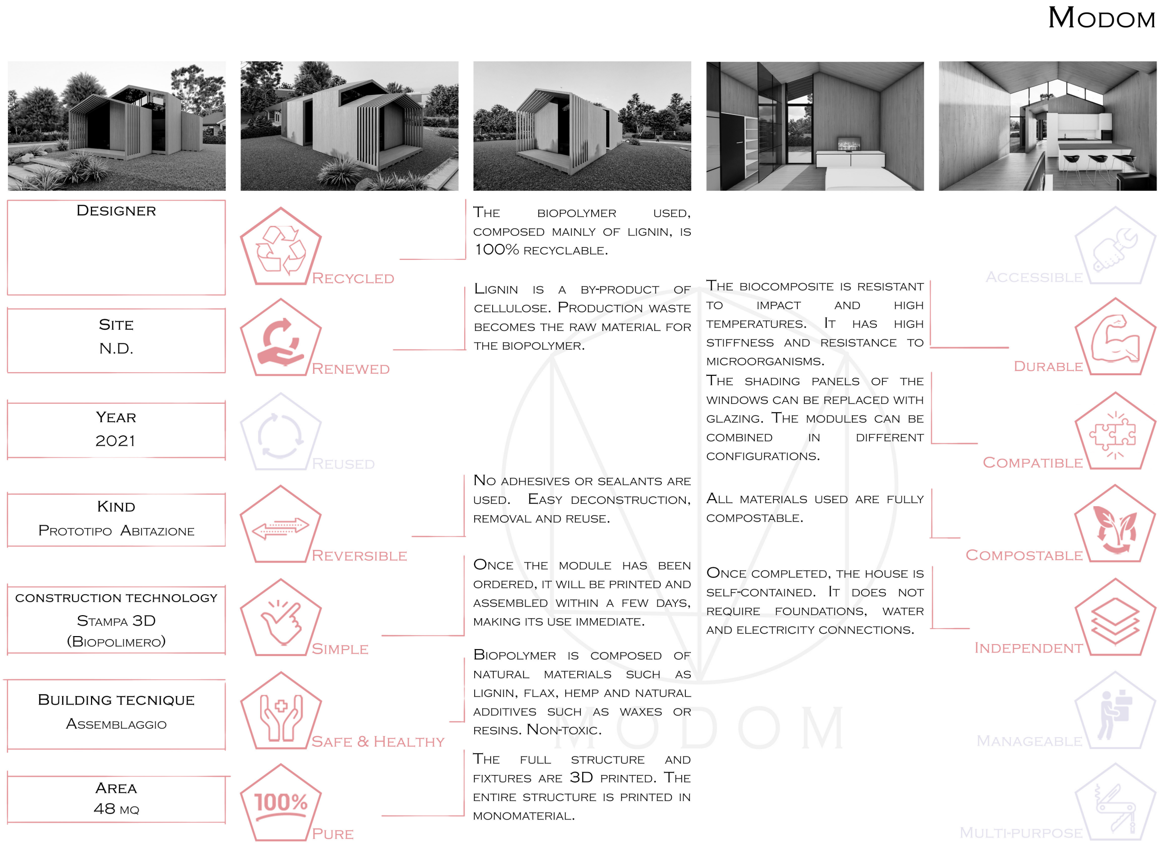

FIGURE 6. Critical analysis of the "MoDom" through Circular Design Qualities (VUB).

	Initial costs	Furniture	Operating costs	Maintenance and Repair	End of Life	TOTAL
Traditional Construction	550.00 €/m^2	110.00 €/m^2	450.00 €/m^2	700.00 €/m^2	190.00 €/m^2	**2 000.00 €/m^2**
MoDom	830.00 €/m^2	90.00 €/m^2	280.00 €/m^2	200.00 €/m^2	100.00 €/m^2	**1 500.00 €/m^2**

TABLE 1. A Quantity of Life Cycle Cost.

lignin, in fact, comes from a recycling process of production waste;

- "durable" through the ability of the material to maintain the characteristics for which it was designed over time.

A further aspect to be considered for the design of a circular building is that the construction solution using 3D printing can significantly impact the cost of the entire life cycle. In anticipation of the production of its full-scale prototype, the evaluation carried out on the project shows how MoDom can guarantee savings of up to 25 % of the total cost compared to construction using traditional technologies.

Based on data from technical literature (regarding the costs of traditional construction) and empirical data (regarding the costs of buildings realised with the Additive Manufacturing technique) [21], the following parametric cost quantities per m^2 in the life cycle were defined (Table 1). The increase in initial costs is amortised during the extended life cycle phase. Specifically, the costs are amortised during the use phase, both in management and repair, thanks to the connection techniques and systems that have a significant impact, together with the material used. Finally, the estimation accounts for the halving of costs to the end-of-life scenario, allowing a closed cycle of use and reuse.

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