La Petite Cabane: the flexible and circular technological structure

Design process innovation through flexible and circular technological solutions

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Abstract: The goal of optimizing material resources and the polyvalent use of space lead to the development of new technologies within a renewed architectural spatiality, which from the point of view of effectiveness of choices allow for low-carbon buildings. The climate emergency, in fact, asks us today to reinterpret Vitruvius' concept of *Firmitas* according to the criteria of durability reliability and resilience associated with widespread usability functionality and circularity (*Utilitas*) traceable throughout the life cycle a building. The paper illustrates the results of a scientific research project that led to the construction of a prototype of a "minimal" residence, designed and built with the "total low" approach, characterized by regenerative design, economy, lightness, ease of assembly, recyclability, as well as excellent overall performance and high levels of comfort. The idea of a building, easily assembled and disassembled, is a strength of the "Petite-Cabane" design concept: a 3x3 m single-user minimum residential unit made with the Light Gauge Steel Building System (LGS) produced with controlled automatically roll forming machine, for which high technological and energy performance envelope packages. The design of a small house becomes the "mise en forme" of a space in which "essential" equipment, energy performance, architectural qualities, economic and environmental costs are linked to the ease and immediacy of construction but also to the flexibility and circularity of technological choices.

Keywords: circular construction; technology flexibility; carbon neutral building; human-centred design; environ-centred design.

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1. Introduction to the technical and cultural background

The goal of creating buildings that are functional, comfortable and at the same time climate-neutral obliges us to make a paradigm shift in the design approach that aims to contain the resources used and waste produced throughout the life cycle, to be flexible in the way we conceive architectural spatiality and to ensure the circularity of the adopted innovative technological solutions.

In fact, it is necessary to reconsider the role of matter in the design process, with all its morphological, ecosystemic and fruitive quality. But to these, technological and environmental quality must certainly be added; they are transformed into as many levels of feasibility until a complex, but not overall, result of "Possible Quality" is achieved in which limits are variable from place to place, from case to case. In this fluid society, continually seeking technological innovation and in constant transition, the benefits induced by aesthetic and emotional quality (traceable to Vitruvian Venustas) are not negligible. They constitute a real added value that is immediately perceptible and communicable.

Then, the Vitruvian triad of *Firmitas*, *Utilitas* and *Venustas* can also be reinterpreted through the canons of contemporary materialism, which entrusts the material, as well as the (architectural) system, with the role of responding to specific efficiency requirements. Thus, the material must be durable, reliable and resilient (*Firmitas*), widely usable, functional and circular (*Utilitas*) and finely workmanship, integrable and innovative (*Venustas*). But it must also have the added value of aesthetic appeal as well as morphological reliability, eco-compatibility as well as innovation, being low cost, low emission and carbon zero as well as recyclable.

This requires profound innovation in technical aspects, new recycling methods and innovative eco-design, but also new logistical concepts, product traceability and alternative business models, right up to the redefinition of technical requirements (mandatory standards).

Thanks to technological innovation, which has experimented with highly efficient materials and high-performance building systems, even the issue of mass, to which the energy performance of the envelope was linked until recently, is conceptually redefined. One of the main rules for reducing the carbon embedded in buildings is to reduce the amount of material used in a construction, as this leads to a reduction in the environmental impacts of the project itself (D'Amico & Pomponi, 2018).

According to EU Regulation 2121/1119, the reduction of greenhouse gas emissions by 2050 must be 90 per cent, but if considering the carbon impact of the construction sector, this target can never be achieved, except for 62 per cent if only direct emissions from heating, cooling, ventilation, lighting and domestic hot water production are considered (Verhagen et al., 2022).

Considering also the 'embedded grey emissions, from cradle to gate' due to the materials used (especially envelope materials, particularly insulation) will reduce carbon dependency (carbon footprint), recycle carbon from biomass and waste (negative carbon emission) and remove excess carbon (embedded carbon neutrality), which are the three cornerstones of technological innovation for a true ecological transition of the built environment. Bio-based materials are a solution for sustainable and durable carbon storage.

Therefore, in order to significantly reduce both operational and embedded energy and carbon emissions of building materials, for the same thermo-hygrometric performance, nature-based solutions should be preferred, whose life cycle assessment has shown drastically reduced net carbon emissions during the entire production process compared to a traditional building material. Embodied carbon coefficients (ECCs) are expressed in kg of CO_2e ($kgCO_2e$) per kg of material (kgm), where CO_2e represents the carbon dioxide equivalent of greenhouse gases (GHG) produced for the production and transport of these materials (Florentin et al., 2017).

The recovery of high-quality materials contributes to reducing environmental impact through subsequent reuse, repair, remanufacturing, and recycling and maximize economic value (Ferreira Silva et al., 2020), implementing a paradigm shift.

The use of prefabricated and industrialized products and systems can help provide greater control through an environmental assessment from their manufacture to end of life (LCA). (Ramos-Carranza, 2021).

In this context, especially in the construction sector, the European Union is calling for a shift from linear to circular systems, and there is an emerging need for a radical change in the way buildings are designed and constructed, leading to the implementation of circularity in the entire process, controlling inputs and outputs throughout the life cycle, with particular attention to the construction and end-of-life phases and the management of construction and demolition waste, which should be considered as a resource.

Figure 1 | The Petite Cabane.

2. The technological concept: Circular thinking

On these technical and cultural premises, the industrial research project "3X3 Zero Energy Building" is based. It is conducted by the Research Group "Carbon Neutral Buildings" (CNB) of the Department of Architecture and Industrial Design of the Università della Campania "L. Vanvitelli" which has produced a prototype of zero energy building, which demonstrates the thesis that the good final result is born in the concept of the project and in it is preordained: "La Petite Cabane" (Figure 1).

The dialogue of reciprocity between technological innovation and architectural space invites a renewed need for flexibility and adaptability, responding to a dual concept of human and environment-centred construction.

Buildings are designed to meet the needs of current and future generations and to be updated and transformed to "adapt to posterity"; but they are also designed to be disassembled and recycled, to reduce the consumption of raw materials and increase the useful life of buildings in a circularity perspective that guarantees a low carbon footprint.

"La Petite Cabane" is a building with a highly technological contemporary design concept through both the use of strategies that aim to reduce the amount of material used and waste produced, ensuring optimal performance (Ferreira Silva et al., 2020) and the technological flexibility of envelope solutions that can be adapted according to different uses, environmental context and climatic conditions. In fact, starting from the wide range of spatial configuration possibilities, it can easily be adapted to future needs as it can be quickly disassembled and reassembled.

The idea of temporary building, which can be easily assembled and disassembled, can be an interesting cue and should be updated in light of environmental issues through the use of strategies that aim to reduce the materials and waste produced. (Violano & Cannaviello, 2022) The idea of a "new building typology and design process" had already been proposed in some research whose evolution "could potentially lead towards an innovative and progressive architecture described as Renewable, Adaptable, Recyclable and Environmental (R.A.R.E.)". (Luther et al., 2006).

Many studies show that the design phase is the most effective in creating the preconditions for reducing the carbon footprint in the cradle of the production process, minimizing consumption in the operational phase, and maximizing reintroduction into a new Biological and/or Technological cycle (McDonough & Braungart, 2010) in the end-of-life phase (Ekanayake & Ofori, 2004; Akanbi et al., 2019).

However, current practice still takes into very little consideration at the initial stage "how, at the end-of-life (EoL) phase, the building and its materials can be deconstructed or disassembled in order to design out waste or minimize the waste stream (Kanter, 2018).

The "Petite-Cabane" is a 3x3 m single-user Minimum Residential Unit built with the Light Gauge Steel Building System (LGS). It is an experimental prototype documenting research on technological design based on circular construction, adaptability and flexibility requirements, standardization techniques through digital production and the use of materials and components with high technological and energy performance.

3. Research phases and technological design guidelines

La "Petite-Cabane" is the result of the first phase of experimental design of the research, formalized with an agreement with LSF Italia srl and with the participation, in the prototype realization phase, of ten other industrial partners who are financial sponsors. The entire research was divided into five phases (Figure 2):

- WP1/KC Knowledge and Consciousness
- WP2/DE Design and Experimentation
- WP3/TC Theoretical Check (Review)
- WP4/LT Laboratory Test
- WP 5/E Enterprise

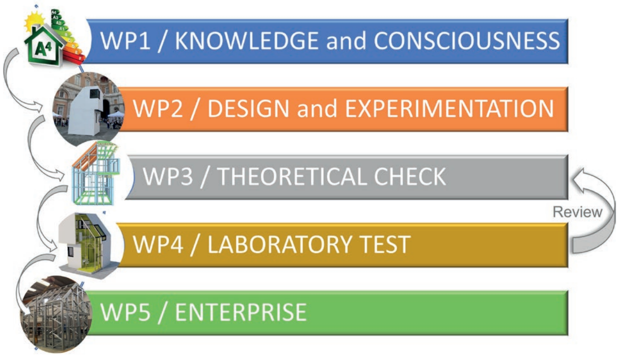

Figure 2 | The research phases.

And the studies carried out were aimed primarily at minimizing the energy-environmental impact of both the individual component and the building-installation system as a whole (Violano, Capobianco, & Cannaviello, 2021).

The design and Experimentation phase (WP2/DE) started with the architectural and technological design of the building envelope components, structure, and systems in relation to the criteria explained below and summarized in Figure 3.

The design was developed in accordance with the regulatory requirements of a carbon zero building preferring for the envelope solutions the use of recycled, low carbon and energy materials and nature-based solutions, maximizing the percentage of biobased materials. In particular, the design of the envelope is experimental and conceived as a system with interchangeable layers (study of the system of connection between layers) conceived with a basic component, strongly integrated to the structure, with high thermal resistive performance and a series of additional external and internal layers with capacitive thermal characteristics, varying in relation to specific needs (climatic context, regulatory requirements, integration of renewable sources, etc.). In fact, the materials study was done through a balance between the energy benefits in the operational phase and the carbon embodied in the process cradle, calculated under three different possible climate scenarios (Violano, Capobianco & Cannaviello, 2021).

The technological choices of the envelope stratigraphies also maximized the reduction of the quantity and weight of materials used, managing to achieve with minimum thicknesses significant performance.

LIFE CYCLE stage	PROCESSES	GOALS	USED STRATEGIES	Reduce demand	Reuse existing	Circular design
PRODUCT stage	Extraction and production of Materials	Reduce the quantity and weight of used materials	Designing to minimize/optimize dimension of living spaces	●		
			Optimizing the steel quantity through the Computer-Aided Prefabrication for the structure	●		●
		Use of recycled materials	Using of recycled steel for the structure	●	●	●
		Use of Low embodied carbon materials	Using of low-carbon materials for the envelope	●		●
		Use of Nature based solutions	integrating innovative bio-based materials for the envelope	●	●	●
CONSTRUCTION PROCESS stage	Transport to the site	Optimize the size and weight of the materials used	Reducing quantity of material	●		●
		Minimize the distance to the construction site	Using materials produced less than 150 km away	●		●
	Pre - Assembling of components in factory	Reduce energy need	Not using heavy handling and lifting equipment, nor welding machinery	●		●
	Site preparation	Reduce noise, vibration and ground movement	Using a quick and low invasive foundation system	●		●
	Construction processes on the building site	Reduce time and energy need for construction processes	Using pre-assemblated component	●		●
		Reduce waste on the building site	Using dry construction system		●	●
USE stage	Operation of building incorporated systems	net Zero Energy Building	Optimizing Thermal insulation and thermal inerthia	●		●
			Optimizing efficiency of thermal and electrical systems	●		●
			Integration of renewable, thermal and electrical sources	●		●
END OF LIFE stage	Demolition	Reduce the amount of materials and components to be demolished	Use building systems that can be disassembled rather than demolished	●	●	●
	Reuse, Recycling	Maximize the percentage of recyclable materials	Structure and Envelope are decostructed and reusable/recyclable	●	●	●
		Design for Disassembly	Structure and Envelope are disassembled	●	●	●
	Final Disposal	Reduce C&DW	Minimizing the amount of C&DW to be landfilled	●	●	●

Figure 3 | Process phases, goals and strategies in Life Cycle stages of the "Petite-Cabane".

Also with regard to the structure, through digital tool-assisted prefabrication and the study of digital twins (Figure 4), the solidity and stability (*Firmitas*) of the building system was ensured with minimal use of steel in order to increase the potential for circularity and environmental compatibility of the building system. In fact, it has been shown that most of the embodied energy and carbon in buildings is attributable to the supporting structure, especially when it is made of steel (De Wolf et al., 2017).

The choice of system type, materials, and installation methods (level of separability), also took into account embodied energy and expected lifetime; the design of thermal and electrical systems optimized efficiencies to reduce non-renewable primary energy requirements and maximized the potential for integration of renewable, thermal, and electrical sources.

Finally, in the last phase of the building life cycle, recyclability and/or reusability of components is ensured in

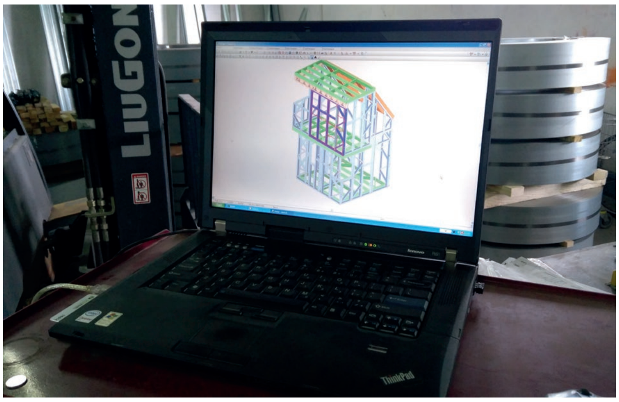

Figure 4 | Use of digital tool- and digital twins.

relation to the ease of disassembly and/or disassembly of the entire building-plant system (Design for Disassembly).

The goals constitute the centrality of the design phase (WP2/DS) that led to the realization of the prototype (Figure 5). In this contribution we want to highlight the feedback phase following WP4/LT.

The Laboratory tests allowed us to define the design strategies to improve WP3 in order to design a building that goes beyond the nZEB and CNB strategy, but that follows the Circular Building approach (Figure 6).

The prototype served, in fact, to move forward in the theoretical ceck thanks to the additional data collected during the de-construction and reuse operations.

In fact, in relation to point 6, different approaches have been studied to manage the reuse phase, aiming to maintain high quality of recycled materials, thinking not only to the minimization of environmental damage due to the reduction of waste in landfills, but also to the benefit due to the maximum amount of material reintroduced in a next building production cycle.

The innovative construction process, featuring rapid and easy assembly, as well as extreme technological flexibility and recyclability, made it possible to create homes with a recycled press-formed steel structure and flexible, lightweight envelope that provides excellent overall performance throughout the life cycle.

Finally, the “human centred” and “climatic centred” design has made it possible to create liveable spaces conceived with a “tailor-made approach”, not only from a functional point of view, but also from a performance point of view.

In particular, “the most important innovation presented is on the building envelope scale.

The research for the optimisation of the stratigraphies aimed at minimising the thickness and quantity of material used, while complying with the minimum requirements of the current standard, has not only economic implications (sometimes minor), but it has an undoubted weight on the carbon footprint and environmental costs at the end of life.” (Violano, Capobianco & Cannaviello, 2021).

The strengths of the experiment are, in fact, the lightness (the prototype weighs 800Kg), the speed of construction (2 days) and ease of assembly (4 hours

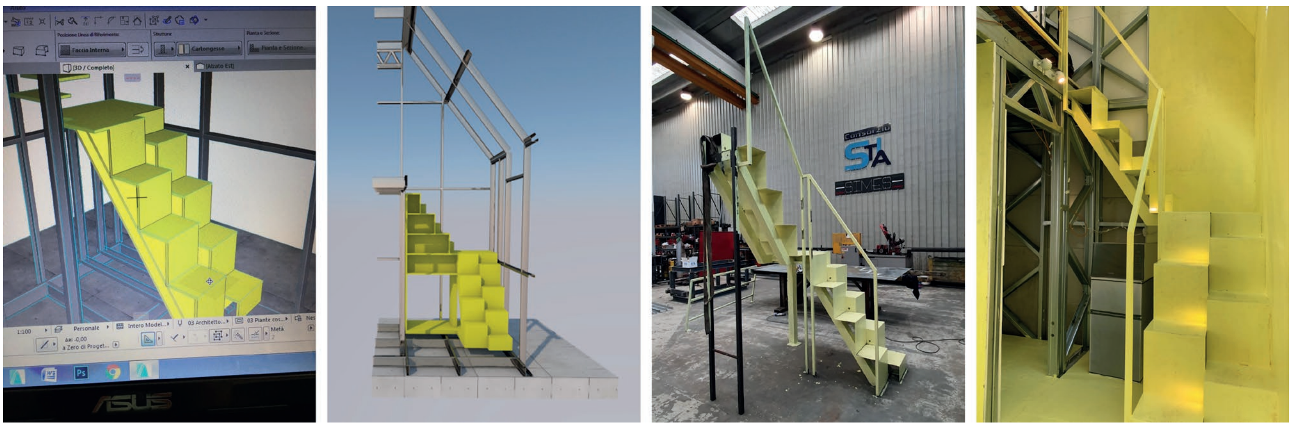

Figure 5 | Design study.

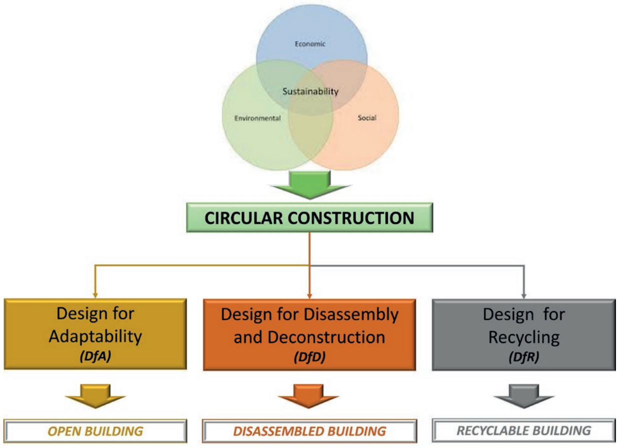

Figure 6 | The circular construction approaches.

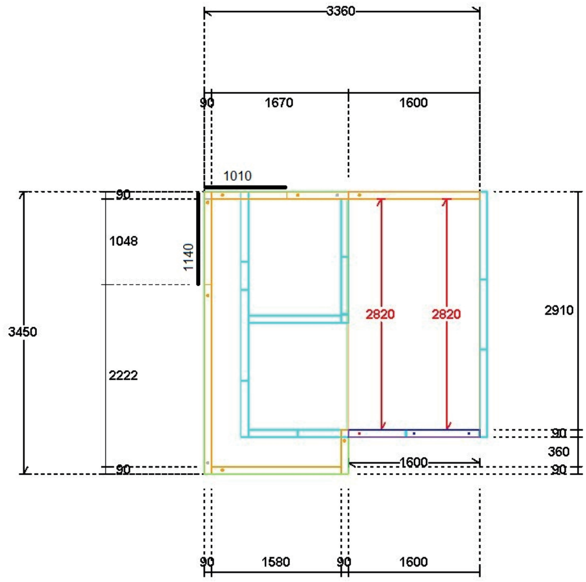

Figure 7 | Computer-Aided prefabrication for the planimetry of the "Petite-Cabane".

by unskilled workers), as well as the extreme flexibility of design (adapted to the user) and eco-compatibility (materials and components meet the rules of the "Cradle to Cradle" approach.

The real competitiveness on the market is given by the eco-oriented high-performance intelligent envelope, able to meet all energy-environmental needs. In this context, the technological choices, related to the construction system, components and materials, take on a strategic importance, as well as the design, production and construction methods must evolve to adapt to the renewed needs, in a global logic of regeneration that allows the circularity of the process marked by the "total low" even beyond the life cycle.

3.1 The total low approach

Blaine Brownell defines "Right-sized" as one of the main strategies for developing a truly sustainable and recognisable architectural design: "One of the most commonsense approaches to ecological building is to size components and structures appropriately. Materials and systems should not be over-engineered, and the space provided should not exceed the intended occupancy." (Brownell, 2018) In the realised prototype, the components are truly "right-sized" and "tailor-made" in order to guarantee a cost-effective product, whose realisation requires the minimum use of resources, whose type of materials used are low carbon and low emission, even low energy for standard uses (embodied and operational), meeting the criterion of 'total low'. (Violano et Cannaviello, 2021)

In fact, the "total low" approach is based on: low costs of production, low environmental impacts (according to the European Environmental, Health and Safety Guidelines) and minimum production of wastes and CO_2 emission; so they intend to overcome the threshold of competitiveness, offering a product that is not only eco-sustainable, but also economically convenient, for both the producer and the ending user. A new way of thinking about the innovation of a product, less impacting from an ecological point of view and that can be reintroduced at the end of its bio-lifecycle according to the Cradle-to Cradle approach (Violano, Cannaviello & Del Prete, 2021).

The new material culture therefore leads the technological design process to search for the right dimension of the component.

It is a methodological challenge that emphasises the designer's role in systemising a profound knowledge of the performance of materials, control of the relationship between physical characteristics (density, surface mass, conductivity, vapour resistance factor, specific heat, etc.) and performance, familiarity with the use of digital tools and the sensitivity to dynamically interpreting the relationship between needs and requirements that arise from time to time, translating these inputs into an appropriate and effective design solution (no longer just efficient).

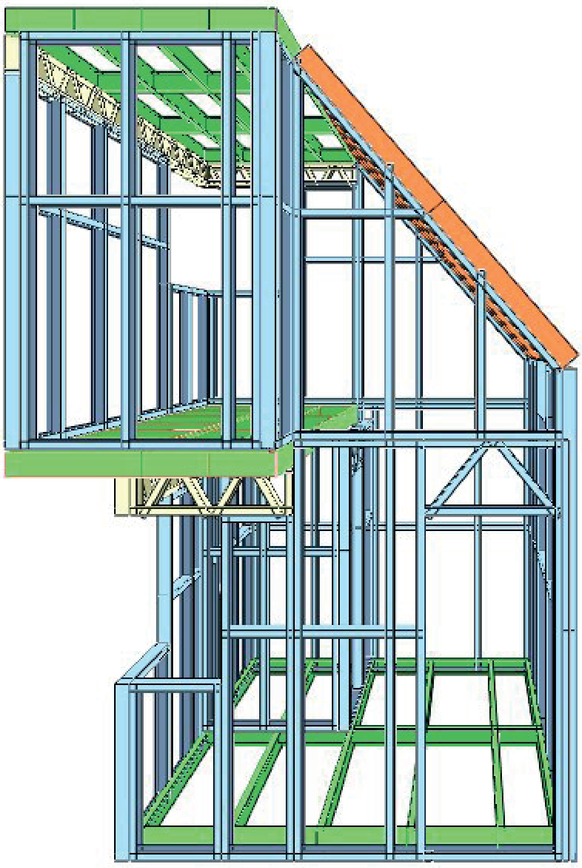

Figure 8 | Computer-Aided prefabrication for the structure of the "Petite-Cabane".

It is a true "technological intelligence" that does not limit itself to managing the relationship between needs, requirements and performance in a technological way but controls the design process with a "risk thinking" approach and goes beyond the mere instrumental control of physical parameters: it learns from the empirical experience of the past, combines it with the architect's own spatial skills (Gardner, 1996) and transforms them into innovation.

4. The technological design objectives

On the basis of these assumptions, the technological design of the 'Petite Cabane' prototype, in line with the 'circular building' approach, was based on the use of prefabricated modular elements that can be dry-assembled and combined in different ways to generate buildings and formal and spatial solutions that differ from time to time according to the specific needs of the user and in relation to the microclimatic context in which they are to be located. "Technological flexibility" and "Circularity " are the main keywords of this idea focused on comfort and carbon footprint reduction. The classic concept of a technologically static environment is abandoned: the dynamic, ever-changing space adapts to the needs of everyone who uses it. Because the prototype is based on fully prefabricated modules that can be easily assembled and disassembled, the space can be rapidly incremented, modified, and adapted to changing needs and context in a timely and cost-effective way.

The "Petite-Cabane" has been designed and built to be adaptable, didassemblable and recyclable according to the needs of future society. The technological design has been set up to guarantee spatial and constructive flexibility during the expected useful life and the possibility that the single elements can be disassembled and later in another place reassembled/reused/recycled.

The technological design of the prototype was inspired by different approach (Figure 6): Design for Adaptability (DfA) (Gelderman, 2016), Design for Disassembly and Deconstruction – DfD (Akanbi et al., 2019; Akinade et al., 2017; Cruz Rios et al., 2021), Design fo Recycle (DfR) (Luther et al., 2006; Ferreira Silva et al., 2020), which are closely related to each other.

> "Design for Disassembly (DfD) and Design for Recycling (DfR) are two such methods that gained ground in the building sector. DfD and DfR focus on recyclability from a technical design point of view, aiming to reduce the negative environmental impacts of construction". (Gendermans, 2016)

> "Deconstruction is the process of dismantling a building in order to salvage its materials for recycle or reuse. [….] Also known as "construction in reverse", deconstruction is a newer terminology for an old practice." (Cruz Rios et al., 2015)

The development of these approaches pursues the goal of optimizing resource use by closing the construction materials cycle. In fact, it aims to reduce material consumption, costs, and waste from construction (Ajayi, 2017), renovation, and demolition, and eliminate waste that cannot be fed back into the cycles. "The aim to include the disassembly, reuse, and recyclable concepts in the design process is to reduce resource and energy use throughout the building life-cycle." (Ferreira Silva et al., 2020).

Figure 9 | Standardization of components and dimensions and modular structure.

According to these approaches, materials, components of the envelope, and the innovative lightweight press-formed steel construction system in LGS Construction System, produced with Controlled Automatic Roll Forming Machine, were chosen. They constituted the added value for the disassembly as well as for the decarbonization of the building system. We, in fact, started by identifying the requirements of regenerative architecture, which in a proactive way could reverse the trend of environmentally harmful design choices, in order to favor technological solutions that even in the long period would have a positive overall net impact (Attia, 2018; Mang & Reed, 2020).

The following objectives were implemented in the Petite Cabane:

1. use of standardization of components and dimensions and modular structure (Figure 9) according to the "open building" principle (Gelderman, 2016);

2. use lightweight materials and components (Cruz Rios, 2021);

3. design a flexible, adaptable building (Cruz Rios 2021; Gelderman, 2016);

4. use of accessible connections and junction methods to facilitate disassembly according to the logic of the "Demountable Building" (Fereira Silva et al., 2020);

5. use of mainly recyclable materials according to upcycling criteria and/or reusable. These materials must also be separable from non-recyclable, non-reusable, and non-disposable materials (Fereira Silva et al., 2020; Gelderman, 2016).

The technological flexibility required of the prototype is thus intended in relation to the entire life cycle and beyond: the building elements and materials at the end of life must be able to be transformed into resources for other buildings, minimizing the consumption of construction and demolition waste.

For these reasons, the overall goals of the experiment, both resource optimisation and waste reduction, were identified in relation to specific life cycle phases. For each phase, the processes on which it was deemed appropriate to intervene were defined. For each goal, the main strategies implemented were described (Figure 3).

In the product phase, the goals related to the Process of "Extraction and production of Materials" are:

- Reduce the quantity and weight of used materials
- Use of recycled materials
- Use of Low embodied carbon materials
- Use of Nature based solutions

In the Construction Process stage, the goals related to the Process of "Transport to the site" are optimize the size and weight of the materials used and minimize the distance to the construction site.

For the Process "Pre-Assembling of components in factory" (Figures 7-8), the goal is to reduce energy need, attributable to the construction process.

For the Process "Site preparation", the goal is to reduce noise, vibration and ground movement.

For the Process "Construction processes on the building site", the objectives are the reduction of energy for construction processes and the rationalisation of construction site waste.

In the Use stage, the goal related to the Process of "Operation of building Incorporated systems" is to reduce the non-renewable primary energy demand complying with the minimum requirements for a net Zero-Energy building.

In the End of Life stage, the goal related to the Process of "Demolition" is to reduce the amount of materials and components to be demolished.

For the Process of "Reuse, Recycling", the goals are maximizing the percentage of recyclable materials and design for disassembly.

For the Process of "Final disposal", the goal is reducing C&DW.

Starting from these goals, the strategies to be applied for the technological design of the 3x3 house have been defined, structured on three strongly interconnected levels:

- Reduction in the demand for non-renewable resources.
- Reduction of waste and reuse of materials.
- Circular design.

5. The implementation of strategies

The design examined flexibility as a fundamental requirement to be incorporated into the life cycle of buildings, using strategies that address not so much the form as the technological system that governs it. Technological flexibility, understood as the ability of a system to be easily modified and to respond to changes in the environment in a timely and cost-effective manner, can be considered the antidote to obsolescence, i.e., the characteristic of the system that ensures slippage over time. With careful selection of building materials, designing for flexibility requirements aims to pursue environmental sustainability (Cellucci & Di Sivo, 2014).

The strategies implemented in the different phases of the life cycle of the 'Petite-Cabane' to achieve the objectives of technological flexibility and circularity defined in the meta-design phase, aimed at reducing the demand for resources (materials, energy, space, time, soil) and the production of waste (Figure 3).

The experimentation associated with the design and implementation of the prototype, as well as its De-construction, confirmed that most of the strategies used, in addition to being effective in containing resources, contributed to the creation of a circular building.

Technological experimentation for the realization of the full-scale prototype, to fulfil the goal of Reducing the quantity and weight of materials used, related to the Process of "Extraction and production of Materials" (Product stage), started from the study on the "minimum" dimensions of the functions related to domestic life, which represented the prerequisite to design and build a minimum residential unit (3x3m) able to meet the basic needs of the user with a minimum living area.

A construction system, using the latest technology of cold-rolled light steel profiles was used in order to achieve the set objectives, which contributed to the realization of a flexible and highly efficient space (reducing steel consumption) with a minimal footprint.

The load-bearing structure of "Petite-Cabane" is made with cold pressed galvanized steel (CFS) profiles with the LGS (Light Gauge Steel) system. Galvanized sheets with a zinc layer 275 g/m^2 are used in production to create profiles of 140 mm thick and material thickness is 0.8-1.2 mm (source site LGS - Materials) (Violano, Cannaviello & Del Prete, 2021).

The computer-aided production and prefabrication system (Figures 4-5-7-8) has represented one of the strengths in achieving the goals set, allowing to engineer the structure as a tailoring process. A specific software and a numerical control machine have dimensioned and realized the structural elements in relation to the specific design requirements dictated by the needs of the users in terms of intended use, size, climatic context and orientation.

The contribution of computer-aided manufacturing can result in benefits at different stages of the life cycle, both in terms of reduction of resources used and in terms of waste reduction (Finch et al., 2019).

The digitization of both the design process and the product has allowed for the creation of a prototype that is extremely flexible and adaptable to meet user demands, not only current ones, but also future ones.

The construction method used allowed to reduce considerably the time of the construction process, as well as to ensure great mechanical precision and ease of assembly of the metalwork, curtain wall elements and steel roofing.

Always to reduce the impacts related to the Process of Extraction and production processes of Materials, recycled steel was used for the structure, in the quantity strictly necessary.

One of the main environmental advantages of this construction system is the optimisation of the relationship between resistance and weight of the structure (*Firmitas*): the whole structure of “Petite-Cabane” weighs only 800 kg!

The steel profiles, made with the prefabricated system, were delivered separated and pre-assembled off-site in the necessary components (walls, floors, ceilings, roofs), to reduce the impacts linked to the construction phase (related to energy consumption and C&DW production), but also to facilitate the assembly and disassembly process.

In addition to being 100% recyclable, the structure is designed to be easily and quickly not only assembled, but also disassembled, as all connections are reversible and can be deconstructed. Chemical and welding connections have been almost completely eliminated, using mainly bolted, screwed and nailed connections to facilitate disassembly.

The prototype was built without the need for specialised workers (for the construction 4 hours of work from 4 unskilled workers have been enough) as it can be assembled according to the ‘do-it-yourself’ principle. This method of construction, whereby controlled and precise components are produced for installation on site, allows the user himself to be involved in the process of creating the product to achieve the required customisation. This is consistent with the consideration that “the instinct “play to build” must be the great incitement to be exploited in the twenty-first century and that self-building can be used as a process not only to build our homes, or at least some parts of them, but also to be able to adapt them over time to the specific needs that intervene during the life cycle (Lozano et al., 2019).

Customisation has also made it possible to minimise manufacturing waste, with major benefits in terms of containing C&DW.

For the building envelope, the use of bio-based regenerative materials was also studied.

From a stratigraphic point of view, the envelope components were designed according to the nZEBox approach (Cannaviello, 2019).

Building envelope is made with a series of prefabricated and modular components for the vertical perimeter walls and for the roof, flexible and adaptable to the needs to ensure compliance with energy efficiency and comfort requirements. The overall stratigraphy is composed as follows:

- Support layer.
- Thermal control layer that must ensure regulatory requirements for insulation and thermal inertia.
- Exterior cladding layer.

The external cladding layer can perform different functions depending on the specific requirements: solar control; energy production (integration of renewable sources); green facade (integration of nature-based solutions), communicative function.

The components of the technological system are designed to be recovered for future and different reuse. In a regenerative design horizon, in which not only the “operational phase” but the entire process conceived in its circularity and continuity is of great value, being able to guarantee excellent energy performance of the envelope with a thickness of just 17 cm (as in the case of the “Petite-Cabane” prototype) is of considerable importance (Violano & Cannaviello 2021).

The strategies implemented with the design experimentation have also made it possible to optimise the end-of-life phase. In fact, the entire design is in line with the logic of Design for Deconstruction, the process according to which when a building is demolished, it is feasible to restore d’ll use of the demolished materials (Cruz Rios et al., 2015).

6. Conclusions

For construction to be truly circular, it is not enough for buildings to be flexible and adaptable, according to the logic of Open Building, but the quality and recyclability of the materials used, as well as the connections, are also determinant. From a circular design point of view, the real value of a product is at the intersection of intrinsic and relational properties. This value, defined by multiple parameters, is not absolute [...] In separation, neither intrinsic nor relational properties have decisive significance with regard to circularity; it is on the crossing where fulfilment is created (Gelderman, 2016).

The experimentation that led to the construction and subsequent de-construction of the prototype of the "Petite-Cabane" has shown that most of the strategies**,** implemented during the design and construction phase to reduce the demand for materials and energy and to reduce the embedded carbon, were also effective with respect to the logic of the Circular economy.

In conclusion, the research conducted has led us to deduce and demonstrate that a zero-energy building, for which the materials and components have been selected according to the carbon neutral approach, can also be considered a circular building.

The design of a small house becomes the 'mise en forme' of a space in which 'essential' equipment, energy performance, architectural quality, economic and environmental costs represent the elements of dialogue between a renewed human-centred architectural space and a high-performance offer of environment-centred technological solutions.

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