THE FUTURE NOW: An adaptive tailor-made prefabricated Zero Energy Building

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Abstract. How much space do we need for living? In a backcast vision, the living scenario is inscribed in spaces for short stays, concentrates functions strictly necessary to the daily needs of its occupant, and takes the archetypal shape of the "refuge", naturally inspired but technologically advanced. (Robinson 1982). The contribution proposes results of an experimental technological design conducted by the "ZEBtwdZEEB" research group of the University of Campania "L. Vanvitelli", in collaboration with industrial partners, which led to the construction of a prototype of a zero energy building (3x3m single user residential unit), built with the innovative LGS Construction System in cold-formed steel. Various envelope solutions, which ensure high energy performance, have been designed for it.

Keywords: Zero Energy Building; Adaptive Technology; Embodied Carbon; Light Construction; Human-centred Design.

La Petite Cabane: the design approach

A consolidated tradition of scientific studies, in modernity, traces the evolutionary lines of the theme of minimal housing, driven by the need to provide answers to the basic needs of human living. The instinctive search for protection and shelter, points out Marc-Antoine Laugier in his description of the *cabane rustique*, is on the other hand an archaic and primordial action, which in becoming construction and translating into a refuge gives rise precisely to architecture: «Man wants to make himself an accommodation that covers him without burying. Some branches cut in the woods are the materials suitable for his design. He chooses four of the strongest, and raises them perpendicularly, arranging them in a square. Above, it has four more sideways; and on these other sloping slopes, which point together in the middle inclined and joined to form a sort of roof covered with foliage [...] The small rustic hut that I have described thus is the model on the basis of which all the magnificence of Architecture» (Rykwert, 1972).

Imagining a "minimal house" today, in the inevitable tension to the essential that guides the project and with a view to a backcast vision (Robinson, 1982), confronts us with scenarios in which the choices we made must refer to a renewed and extended vision of sustainability, well-being, awareness of the territory, protection of the landscape as well as having to interpret the changing needs of contemporary living. It is not a question of providing only a practical solution to a need but also of trying to graft, through the project, processes and practices that can act as a reference for the whole community in the direction of reduced and more aware consumption of energy and space resources of our territories. Imagining the minimal functions of domestic life, studying their arrangement and reciprocal relationships, imagining the nature and characteristics of the space of the home, also means taking into account its "essential" equipment, its performance, its aesthetic qualities, its economic and environmental costs, and the possibilities related to the ease and immediacy of its construction (Ishida and Furukawa, 2013).

An innovative light steel bending technology, in this experimental design, makes available to the project, after a phase of careful engineering, a "new" construction system substantially based on assembly techniques. The lightness and speed in the production and subsequent assembly of the structures built with this technology are such as to go well beyond the times with which we are accustomed to dealing in the world of construction, and determine a drastic reduction in costs also with regard to the transport logistics of materials needed for construction. Basically we are faced with a modular frame system that allows large free spans, very small thicknesses and unimaginable plant and design flexibility.

A very small space (3x3 m) is the minimum surface necessary to create a technologically advanced envelope experimenting the design of an archaic space, natural inspiration, through the intersection of simple volumes that define one internal space "flooded" with natural light. A bright, comfortable and performing shelter describes the minimum measures for sleeping, eating, studying, taking care of yourself, and also for spending leisure time.

The *Petite Cabane* (Fig. 1) develops on two levels in height. It is precisely the design of the section of the house, in its configuration of a double height, which conceals the minimum footprint of the internal space to give its occupants an unexpected sensation of amplitude. The house is slightly raised above the ground, and its shape recalls the archetypal image of the hut in the inclination of the roof. This research was also developed through the creation of a prototype on which performance tests are currently underway. The use of innovative technologies for its construction refers to multiple areas of investigation, study and further experimentation. In particular, the possibility of resorting to self-construction and achieving energy independence outlines scenarios of great interest as a response to the social and environmental emergencies with which we daily measure ourselves.

The technological design experimentation: method and results

Petite Cabane is the result of research project experimentation entitled "3X3 Zero Energy Building", which is part of the activities of the Research Group " ZEB towards ZEEB " of the DADI Department of the University of Campania "L. Vanvitelli". It has been established with an agreement with LSF Italia srl and the participation of ten other industrial sponsoring partners in the prototype implementation phase. Considering the design process as a complex decision-making process, the principles of predictions and ordinary nature determined choices based on "general validity" and "probabilistic objectivity" criteria until the end of the last century. Such principles were considered immanent characteristics basically for the design choices made at time x, but they have been replaced by the predictive and proactive backcasting approach, due to the need to reverse the negative trend foreseen by visions of 2050, and change the paradigm by acting at time x with choices that are functional to the implementation of future scenarios (at time x + k) desirable through a "long-term technology" that focuses on the right choices in the individual steps of the "cradle to cradle" process. With the

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Tab. 01 |

	Wall Tipologies					
Codex[5]	WS_B.tlv	WS_B.wtl	WS_D.tl	WS_D.wtl	WS_F.tl	WS_F.wtl
Stratigraphy						
Thickness [cm]	15	11	16	13	17	15,5
Thermal Transmittance (U) [W/m²K]	0,318	0,400	0,272	0,281	23,7	0,234
Periodic Thermal Transmittance (Y_{ie}) [W/m²K]	0,100	0,362	0,062	0,23	0.055	0,160
Time Lag [h]	9^h 15'	3^h 16'	10^h 10'	3^h 60'	10^h 40'	5^h 30'
Decrement factor [n]	0,315	0,905	0,228	0,818	0,232	0,686
Superficial Mass [kg/m²]	74,45	41,85	66,55	26,5	58,65	33,05
Resistance [m²K/W]	3,15	2,50	3,68	3,56	4,21	4,28

Tab. 01 | Energy performance of different designed stratigraphies of prototype

Tab. 02 | Energy summer performance of the same stratigraphy with the different positions of layers

	Codex	Stratigraphy	Thickness [cm]	Thermal Transmittance (U)[W/m²K]	Periodic Thermal Transmittance (Y_{ie})[W/m²K]	Time Lag [h]	Decrement factor [n]	Dynamic analysis in summer check	Thermal penetration depth [m]	Tsupl/TsupE
Wall Tipologies	WS_B.tlv_1		15	0,318	0,095	9^h 15'	0,315		0,0056	0,0113
	WS_B.tlv_2		15	0,318	0,145 ↑	7^h 18' ↓	0,476 ↑		0,0390 ↑	0,0176 ↑

| Tab. 02

(EU) Directive 2018/844, the Union is committed to developing a sustainable, competitive, secure and decarbonised energy system by 2050. These elements are part of the design methodology of the "3X3 ZEB " research. The innovative Light Gauge Steel (LGS) Construction System (Fig. 2) has been the added value for decarbonising structural components of the planned building system, as illustrated in the following paragraph.
The research is divided into five phases:

- WP1 / KC_ knowledge and consciousness (1 / KC);
- WP2 / S_experimentation;
- WP3 / TC_theoretical check (3 / TC);
- WP4 / LT_laboratory test;
- WP 5 / E_enterprise[1].

In WP1/KC (the initial phases of the project), we referred to international research, the proposed process and product innovation it is based on. We, therefore, started by identifying the requirements of regenerative architecture, which proactively reverses the trend of all design choices generating environmental damage, and focuses on solutions that have a long-term positive net impact (Attia, 2018; Mang, 2016). The choice of products and materials follows the "Cradle to Cradle" approach (McDonough, 2010), considering their opportunity to be eco-friendly according to their possibilities of reintegration in the biological cycle (biosphere) or the technological cycle (techno-sphere) at the end of their service life. Finally, a Core set of Indicators evaluates the regenerative quality of architecture (Attia, 2018), ecological and carbon footprint (Solis-Guzman, 2015) and reduction of CO_2 emissions without energy sacrifice (Rovers, 2019).
In WP2/S, the design of building envelope components considered the following criteria:

a. optimisation of consumption and emissions during the operational phase (operational energy and carbon reduction);
b. optimisation of consumption and embodied emissions (embodied energy and carbon reduction);
c. recyclability/reusability of the components, also in relationship with the ease of disassembly;
d. choice of materials also in relationship with the embodied energy and carbon (Geiser, 2001);
e. basic component design according to the nZeBOX approach and identification of additional panels in relationship with specific needs (climatic context, regulatory requirements, integration of renewable sources, etc.);
f. design of the envelope system with interchangeable panels (study of the connection system among the panels), also integrating innovative bio-based materials;
f. design of thermal and electrical systems, optimising efficiency in order to reduce the need for non-renewable primary energy; the type of system chosen, the materials and the installation methods (level of separability) also considered the incorporated energy and the expected service life;
h. integration of renewable, thermal and electrical sources; choice of materials through a balance between energy benefits in the operational phase and embodied carbon.

The actual competitiveness of the final product on the market is given by the high performance eco-oriented envelope, which is able to meet the energy-environmental requirements. On a market based on C2C principles, economic growth is separated from the consumption of resources. This includes both the more strictly technical aspects, such as the design of modular products and innovative eco-design in the product stage, and the new reuse/recycling methods in the end of lifecycle stage, but also product traceability and alternative business models, which will redefine requirements (mandatory standards).
Particularly, in the WP3/TC phase, the designed wall solution allows high technological performance, even when it is less than 20 cm thick.
The performance evaluation of the envelope system (tab. 1) has been made in relationship with three different climate zones (B, D, F), both on the individual components, in relationship not only with the Italian standards in force, but also in relationship with the LEED certification system (this phase is contemporary to the WP2 phase), and on the building-plant system of the 3x3 prototype, not only in a steady state (using the calculation method adopted by the standard UNI/TS 11300 and calculating the values with the PAN 7.0 software), but also in a dynamic mode as adopted by the standards UNI EN ISO 52016-1 and 52017-1 on dynamic hourly calculation.
The minimum requirements laid down by Ministerial Decree of 2015/06/26 foresee a Maximum Thermal Transmittance (U) value of 0.43-0.40 W/m²K in zone B, 0.29-0.32 W/m²K in zone D and 0.24-0.26 W/m²K in zone F. This significant variation makes it impossible to design a single stratigraphy valid for all climatic conditions. In addition, since for zone B the duration of the heating season is 121 days, which becomes 166 days in zone D, and 200 days in zone F, with an increase of about 65% in heating days, homogenising performance to the most unfavourable condition means an unnecessary (not to say unfavourable) increase in costs. For an average irradiation of the month of maximum sunshine greater than 290 W/m², the summer check must also be carried out, depending on the surface mass excluding plaster (>230 kg/m²) or, alternatively, on Periodic Thermal Transmittance (Yie<0.1 W/m²K). Therefore, in cli-

01 | The *Petite Cabane*, ground and first floor plans, architectural project by L. Capobianco

02 | The construction system and assembly phases in the company

mate zones A-D, the stratigraphy of the vertical perimeter wall may need an additional stratigraphic element to increase the value of the Thermal Lag. Table 1 shows the main energy performance values of the different designed stratigraphies.
The only invariant element is the high performance thermal insulation layer, which is 9 cm thick and is placed in the C-element of the aluminium structure. Since the embedded carbon coefficients (ECC) are expressed in kg of Co_{2eq}($kgCo_{2eq}$) per kg of material (kgm), the technological solution must minimise the amount of material used. Therefore, the designed stratigraphies follow this concept.
The laboratory test for thermo-hygrometric and environmental performance on the designed individual components of the envelope, the patent for innovative elements and the Certification of performance are in progress, as well as the creation of a spin-off on the existing start-up for which funding is awaited.
Special attention was paid to the evaluation of the summer performance of the envelope components (Tab. 2). In such conditions, in fact, the thermal wave must be not only poorly conductive, but also very massive and with high specific heat, in order to allow the envelope system to transmit weakly. So, the heat received at each layer is stored inside the layer itself without determining a thermal gradient between the layers that favours diffusion. With an external finish made of a material with high conductivity (but also high density and specific heat), the heat flow would be high in the first layer but would not pass through the next. In this experimentation, considering the type of wall WS_Btlv, designed for the most unfavourable summer weather condition, the simple variation in the position of layer 1 (insulation) with layer 2 (wood cement) determines an increase in the depth of penetration of the thermal wave (from 5.6 mm to 39 mm) with a consequent increase of the decrement factor (from 0.315 to 0.476). But the most significant data is the reduction of the summer time lag value (from 9h 15' to 7h18') and the summer value of the periodic thermal transmittance (from 0.095 W/m^{2}K to 0.145 W/m^{2}K), which is no longer verified by law. Therefore, in addition to the alternation of layers (resistance and capacitance layers), the reciprocal position is also significant.

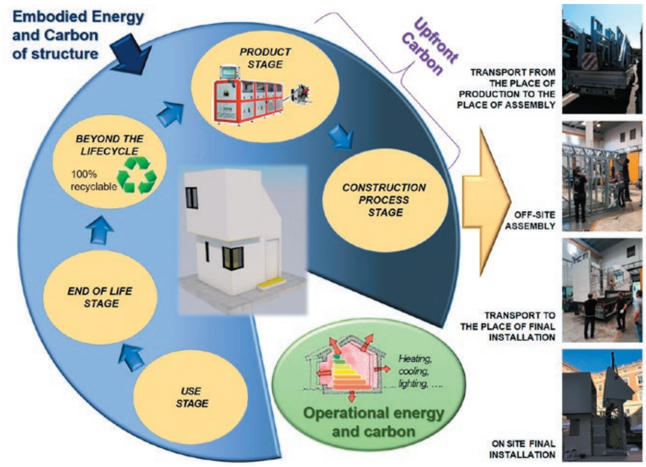
From Zero Energy target in the operational phase to embodied carbon reduction

The targets set by the Report of World Green Building Council in 2019 (www.worldgbc.org), according to which the construction sector emissions should fall to zero by 2050, are not limited to assess the amount of CO_2 emitted during operational life, but they also aim at limiting the amount of Embodied Carbon, which contributes to nearly 11% of all global carbon emissions. Particularly, the emissions associated with the initial Embodied Energy, also defined "*Upfront Carbon*", will be responsible for half of the whole carbon footprint of the new buildings between today and 2050.
Hence, a paradigm reversal in the choice of materials and the con-

01 |

| 02

Tab. 03 | Initial embodied carbon ("upfront" carbon) of the *Petite Cabane* structure



struction process becomes increasingly urgent, favouring the use of innovative materials and processes that effectively reduce the carbon embodied in buildings.
Particularly, the 3X3 Zero Energy Building is not only zero energy in the operational phase, but also net zero embodied carbon in the rest of its service life, with a low "upfront carbon" content.
It has been shown that most of the embodied energy and carbon in buildings is attributable to the load-bearing structure, especially when it is made of steel (De Wolf et al, 2017).
The first step was the analysis of the embodied energy and carbon in the load-bearing structure (Fig. 3), made with cold pressed galvanised steel (CFS) profiles with the LGS system. Galvanised sheets with a zinc layer 275 g / m^2 are used in production to create 140 mm thick profiles with 0.8 - 1.2 mm material thickness (source: http://lgs-montazne-kuce.com/lgs-materials).
Generally, one of the main rules for reducing embodied carbon in buildings consists in using less material (source: Cutting embodied carbon in construction projects - wrap.org.uk).
The use of cold-formed steel for small buildings can result in up to 30% less embodied carbon than hot-rolled steel because cold formed steel frames (for 18 m and 24 m span buildings) are lighter (Johnston et al. 2018).
The production system of the profiles used to carry out the *Petite Cabane* prototype used a Controlled Automatically Roll Forming Machine, which allowed to optimise the quantity of steel used, sizing the structure according to the specific dimensional, formal and structural needs. This avoided pointless oversizing of the middle section of the frames, generally indicated as one of the most frequent inconveniences in the design practice of steel structures (Moynihan et Allwood, 2014), and which increases unnecessary tons of CO_2 emitted. The machine is controlled through a software, which represents the system's core. It simultaneously performs static analysis and sizing. The software simplifies the traditional profile manufacturing process and reduces the additional cuts and relative energy consumption.
One of the main environmental advantages of this construction system is the optimisation of the relationship between resistance and weight of the structure, as this allows to reduce the initial embodied carbon: the whole structure of *Petite Cabane* weighs only 800 kg!

The profiles of the steel structure were carried out in Poland, preassembled in the company for partial spatial elements, and the various parts were assembled within the courtyard of the Royal Palace of Caserta in a very short time (Fig. 4).
In order to evaluate the upfront carbon of the load-bearing structure, in addition to the embodied energy in steel, the energy for transportation and assembly must also be added. The embodied carbon for assembly was nearly equal to zero, as the system does not require any heavy handling and it requires neither lifting equipment, nor welding, nor cutting, nor onsite drilling machinery also because the profiles are already made and equipped with the holes necessary for installation and with service holes for electrical, plumbing and other plant systems. So, it was sufficient to connect them according to the "Do-it-Yourself " principle.
The construction of the *Petite Cabane* prototype structure required 4 hours of work performed by 4 unskilled workers. This allowed to eliminate the energy connected to onsite construction processes.
The life cycle assessment (LCA) approach, used to evaluate the environmental sustainability of the Petit Cabane structure, helped to quantify associated embodied carbon.
The system boundary is from Cradle to Site:

- steel production phase (from cradle to gate);
- transport from the production site of steel profiles to the construction site:
  -rom Poland to the pre-assembly site;
  -from the pre-assembly site to the final destination (Caserta Royal Palace);
- off-site construction (pre-assembly in the factory shed);
- onsite construction (final assembly on the destination site).

Data used for the calculation:

| Tab. 03

Life-Cycle phase		System boundary	Embodied carbon [$kgCO_{2eq}$]
Extraction and manufacturing stage of steel production		From cradle to gate	2.024
Construction phase	*Transport to the site*	From gate to site	1.481
	Of-site construction		Negligible
	On-site construction		Negligible

04 |

04 | The transport and assembly phase of the prototype

- weight of the structure: 800 kg;
- distance travelled between the production site of the steel profiles to the construction site:1,740 km;
- number of trucks used: 1;
- number of trips: 1;
- diesel consumption: 0.325 L/km;
- emission factors of transportation by diesel truck: 2.62 $kgCO_{2eq}/L$ (Yan et al. 2010);
- embodied carbon of steel, cold rolled coil: 2.53 $kgCO_{2eq}/kg$ (ICE Database V3.0 Beta – 7 Nov 2019).

The calculation of the "upfront carbon" of the structure is shown in table 3.

As can be seen from the table, the embodied carbon attributable to transport has a high relevance in the calculation of upfront carbon. However, this criticality can be solved either by creating new production sites closer to the construction sites, or by identifying alternative modes of transport. The off-site construction of the prototype has also contributed to a reduction and better waste management, «On-site construction waste can account for up to 15% of the embodied carbon of a building; off-site construction can significantly reduce this by more than two-fold in most cases» (source: Cutting embodied carbon in construction projects - wrap.org.uk).

Finally, the *Petite Cabane structure* has the enormous advantage of being 100% recyclable at the end of its lifetime, with consequent benefits in terms of "beyond life carbon".

Wall cladding panels have been applied to the structure, suitably designed not only to optimise the primary energy requirement during the operational phase, but also to minimise embodied energy and carbon.

Conclusion

In a future vision of social and energy equity, the building system is designed to significantly reduce not only the energy needs and emissions in the operational phase (energy and carbon net zero in operational phase), but also the embodied energy and carbon. The structure, easily built in all world contexts, even in countries where skilled labour is not present, is designed to be assembled according to the "do-it-yourself" principle. In fact, it offers the advantages of prefabrication without being linked to the constraints that generally characterise prefabricated systems. However, the envelope system varies according to the context in order to optimise performance to the maximum and comply with the binding legislative requirements.

The real competitiveness on the market is given by the high performance eco-orientated smart envelope, which can satisfy significant energy-environmental requirements.

The results of the conception, design, feasibility study (technical, legal, administrative, economic and energy-environmental) phases have been positive. The study phase was followed by the production of the prototype, "3x3 ZEB ... la Petite-Cabane" which was presented at the event "The European Researchers' Night", held on 27-28 September 2019 at the Royal Palace of Caserta (Fig. 5).

The academic Spinoff is being defined. Its objective is to complete the experimentation in order to obtain certification of the system and individual components. At the moment, the main limitation of the research is the acquisition of adequate funding to build all typologies of designed components in order to start the "commissioning phase".

| 05

05 | The *Petite Cabane*, at the European Researchers' Night 2019

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NOTES

[1] The last two phases are being implemented.

[2] The stratigraphic code is defined as follows: Wall Stratigraphy_climate zone. time lag verify or Wall Stratigraphy_climate zone.without time lag verify.

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