Published by Avanti Publishers

International Journal of Architectural Engineering Technology

ISSN (online): 2409-9821

Ecodesign: Green Solutions for Design of Steel Building Envelopes

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ARTICLE INFO

Article Type: Research Article

Academic Editor: Marta Maria Sesana

Keywords:
Eco-design
Steel building
Green building
Low-carbon design
Sustainable envelope
Sustainable construction

Timeline:
Received: February 27, 2025
Accepted: May 25, 2025
Published: July 12, 2025

Citation: Di Ruocco G, Frulio F. Ecodesign: Green solutions for design of steel building envelopes. Int J Archit Eng Technol. 2025; 12: 57-78.

DOI: https://doi.org/10.15377/2409-9821.2025.12.6

ABSTRACT

In recent years, the impact that man has on the environment has become increasingly evident, and the planet itself is starting to re-bel against this great and uncontrolled exploitation of its resources. The need to seek change by approaching a totally sustainable lifestyle is now obvious. Sustainability has in fact become a major player in today's society, infiltrating every area of it, including construction. In the construction field, man's impact is unfortunately inevitable, but it can be mitigated by developing new sustainable technologies, and it is precisely with these that we have had the opportunity to approach a new vision of architecture, arriving at what is called Ecodesign, a way of designing that respects the environment and the resources offered by Nature. The research was conducted on a new building, under construction, within the university campus of Fisciano, Salerno, designed mainly with a steel construction system.

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1. Introduction

Current environmental policies related to climate change mitigation consider the sustainability of human activities, including the construction industry, as an essential strategy [1]. The European Green Deal includes a series of strategic initiatives aimed at guiding member countries towards the green transition. The program, which involves all production sectors and human activities, envisages the achievement of climate neutrality by 2050 with the intermediate objective of reducing CO2 emissions by 55% by 2030. A certainly ambitious project that will involve all sectors of our society, in fact it will deal with safeguarding biodiversity, supporting cleaner energy sources according to the logic of a circular economy [2]. Human activities generate inevitable impacts on the environment that can be direct, such as energy consumption and car use, or indirect, connected to the production, transformation and transport of goods [3]. The construction sector, according to the2022 Global Status Report for Buildings and Construction of the United Nations Environment Programme (UNEP), causes 37% of carbon dioxide emissions and consumes 34% of energy demand globally. To achieve the decarbonisation objectives expected from the recent European directive (EPBD IV) it is necessary to change traditional design paradigms, tending towards a sustainable way of building. This new awareness brings to the scientific forefront important issues such as the energy efficiency of buildings, the circularity of raw materials, and new eco-sustainable technologies. Responsibility towards the environment has led operators in the sector towards experimentation and adoption of sustainable practices, in terms of materials and construction techniques [4]. It is being invested in reducing land consumption, in the energy efficiency of buildings, in the circularity of the raw materials used as well as in the research of new eco-sustainable technologies that can replace traditional construction materials which are certainly more impactful

2. State of the Art

2.1. Ecodesign and the Paradigms of the Circular Economy

The economic model used in production activities is linear (so-called from cradle to grave), according to the logic of conceiving a product destined for its inevitable disposal, at the end of its life. These production systems have led, in the European Union alone, to the production of approximately 2.2 billion tons of waste per year. The awareness of the environmental problem, caused both by the indiscriminate exploitation of non-renewable resources and by the enormous quantity of waste to be disposed of, has led to the development and promotion of a new economic model called "circular economy" (from cradle to cradle), encouraging technological solutions aimed at maximizing the reuse/recycling of products at the end of their life, with consequent minimization of the exploitation of resources for the extraction of virgin raw materials. An essential element of the circular economy is the concept of Ecodesign, which the European Commission describes as "the systemic integration of environmental aspects in product design in order to improve its environmental performance throughout its life cycle" [5]. This means paying attention to all phases of the life cycle: from conception, to design, production, and disposal, each of these must be carried out with the aim of minimizing the environmental impacts generated [3]. The new paradigms of conceiving a work converge towards the principles on which ecodesign is based [6]: the choice of materials, obviously preferring sustainable, recycled and recyclable resources; the reduction of energy consumption, it is very important to prefer a production that has energy saving as its strong point to reduce consumption throughout the entire production process; the reduction of waste, ecodesign requires new technologies that guarantee a long-term durability of the final product which also means a reduction in waste production; disassembly at the end of life, the focus is on composition of the final product making it necessary to use as few different materials as possible in order to simplify future disassembly and recycling; the reuse/recycling of components at the end of life, it is important to think about its second life, the innovation is in the ability to imagine re-adapting something for a new purpose and moving away from the simple idea of consumerism; the use of renewable resources, the last principle could not fail to deal with the use of renewable resources throughout the entire production process.

The number of policies addressing the various environmental impacts of product life cycles is increasing, especially in Europe. With the advent of the Circular Economy (CE) concept, traditional product policies have been joined by new policies that pursue new goals, such as increasing lifespan and encouraging more repairs. The study by Dalhammar *et al*. [7] analyzes principles for improving synergies and reducing conflicts between different product policies. Some of the recent conflicts that have emerged in the context of CE are described, concluding that conflicts can often be mitigated or a compromise can be reached.

A key concept for the circular economy is ecodesign, which considers environmental aspects in product design with the goal of minimizing its impact during its life cycle. The study by Riesener *et al*. [8] presents a framework for forcing the implementation of the “Closing the Loop” and “Slowing the Loop” strategies of the circular economy, using the life-cycle ecodesign approach. It argues how important it is to support the operational implementation of the circular economy through ecodesign. The study by Timm *et al*. [9] lists some recommendations for future work to continue discussions in this area: (i) test the economic feasibility of applying CS (Circularity Strategies) and ES (Ecodesign Strategies) and compare it with traditional practices; (ii) apply CS and ES in different case studies and, preferably at different scales, to test the relationship between increased circularity and reduced impact; and (iii) examine the effects of combining strategies and determine whether there are specific types of buildings, materials or building systems to which they are best suited; (iv) analyze whether there is a particular strategy that should be prioritized or that offers greater environmental benefits based on the phase of the building, whether existing, historic, new, temporary, or other; (v) ascertain how context can influence the application of CS and ES and what factors should be carefully analyzed; (vi) determine how to communicate the levels of circularity (or possible pathways) and its benefits to decision makers; and (vii) determine how to automate the inclusion of strategies in modeling software such as BIM, facilitating the inclusion of the practice into the routine of design offices.

The Ecodesign for Sustainable Products Regulation (ESPR), which entered into force on 18 July 2024, is the cornerstone of the European Commission’s approach to more environmentally sustainable and circular products. Products and the way we use them can significantly impact the environment. Consumption in the EU can, therefore, be a major cause of climate change and pollution. The ESPR is part of a package of measures that are central to achieving the aims of the 2020 Circular Economy Action Plan and fostering the transition to a circular, sustainable, and competitive economy. It will contribute to helping the EU reach its environmental and climate goals, double its circularity rate of material use and achieve its energy efficiency targets by 2030 [10].

For Ecodesign is very important choosing the right materials and attention falls on those that are biodegradable, reusable, recyclable and non-toxic in full compliance with the principles stated above. So, the preferred materials are wood, natural, recyclable, resistant and from a renewable source; aluminum, which can be recycled infinitely; bamboo, considered an excellent alternative to wood; plastic, can be considered a good ally for ecodesign by improving pollution problems mainly related to disposal processes and dispersion in the environment; but also cork, jute and linoleum.

2.2. The Regulatory Framework

In this context, the Ecodesign Regulation for sustainable products, adopted by the European Council on 27 May 2024, is particularly relevant. It is a document drawn up in compliance with the ISO 14006:2020 standard [11], which helps organizations establish, document, implement, maintain and improve Ecodesign management as an integral part of the environ-mental management system [12]. The guidelines of ISO 14006:2020 can be applied to all companies regardless of their sector. The concepts underlying the standard concern the continuous improvement of the environmental management system to im-prove the environmental impact that derives from its products and services; the life cycle of the product in order to pay attention to each phase of its life cycle with respect to the environment; and finally, the prevention of negative impacts generated along the entire production path. The European Directive known as ErP – Energy related Products [13] defines mandatory ecological requirements for the energy consumption of products in all Member States. It applies to over 40 types of products that are responsible for almost half of all greenhouse gas emissions in the European Union by defining the requirements for the design and to allow the placing on the market of any product. The subsequent directive [14] broadens its scope by considering new products, such as those that use, produce, transfer or measure energy, and products that do not necessarily consume energy but still have an impact on consumption and could consequently contribute to energy savings (such as windows, insulation material or taps). Also worthy of attention is the "Circular Economy Waste Package" which includes four directives [15] with the role of modifying the main Community rules on waste by promoting the transition towards the circular economy [16]. The European Union has issued a series of directives aimed at incentivizing the increase of energy performance Energy performance of buildings directive (EPBD). In October 2020, the European Commission presented the Renovation Wave which contains strategies to renovate both public and private building stock, as part of the more ambitious Green Deal plan. The latest EPBD IV directive [17] sets the objective of decarbonising the European building stock by 2050. This directive must be transposed by 29/05/2026 by the Member States, who will have to prepare a national building renovation plan to ensure the renovation of the national stock of residential and non-residential buildings, both public and private, in order to make it zero-emission. In particular, for residential buildings, a reduction in average primary energy use of at least 16% by 2030 compared to 2020 and of at least 20-22% by 2035 must be ensured. For non-residential buildings, Member States will have to set mini-mum energy performance requirements that must be met by at least 16% of buildings by 2030 and by at least 26% by 2033. Subsequently, Member States will have to ensure a progressive reduction in average primary energy consumption until 2050 in line with the transformation of the residential building stock into a zero-emission building stock. New buildings will have to be zero-emission as early as 2030, with an early deadline of 2028 for public buildings.

3. Tools and Methods

The most widely adopted tool, in the international scientific panorama, for the evaluation of the energy-environmental impact of the building, is the Life Cycle Assessment (LCA) which allows to evaluate the impacts of the phases of the life cycle through the quantification, for each of them, of the emissions, with particular reference to CO2e (Global Warming Potential).

3.1. Eco-design Software

The integration of BIM software in the design of sustainable buildings has acquired considerable importance as it has become a valid ally that helps put the principles of sustainability into practice. Through digital models, information relating to the layout of spaces, the use of sustainable materials can be easily evaluated, but above all it helps manage the building throughout its entire life cycle by controlling the resources used in each phase and thus starting a process of procedural, technological and environmental quality. It also allows for full traceability and management of materials, thanks to the possibility of integrating all the information relating to them; to optimize transport with logistics simulations that reduce waste and consequently also greenhouse gas emissions, minimizing the environmental impact; to better manage energy and waste through energy and environmental analyses during the life cycle of the building; to make all the professionals working on a project collaborate and communicate; finally, to produce digital documentation and various certifications [18].

3.1.1. Edificius

Edificius is the BIM building design software proposed by the company Acca Software. Through its use it is possible to create a three-dimensional model of any new or existing project in digital format and directly importing the plan onto the work Table. Designing with this program also allows you to integrate the model into the real environmental context thanks to the possibility of inserting the landscape through the use of Google maps which in this way allows you to better evaluate the visual impact of the project and the environmental impact as well as giving the possibility of also modeling the external spaces of the building. Each component of the building, after being faithfully created with respect to the design idea, can be further characterized by inserting the material it is made of with all its properties and the finishing color thus making the model as faithful as possible to reality and allowing you to also extrapolate all the information regarding its various parts as well as making the metric calculation available. Edificius also offers a large online library where you can find both components such as fixtures and furnishing elements making it also an excellent ally for interior design projects. Finally, it is also possible to model the project's systems simultaneously with the structural modeling, providing an overall view of the project in all its parts in order to avoid interference between the architectural and systems parts (Fig. **1**).

Figure 1: Example of a building made with Edificius.

3.1.2. Termus

Termus is a BIM energy software that allows direct import of models from Edificius via IFC files, preserving all data. It enables the calculation of a building's energy performance and generates documents such as energy diagnosis, APE certification, and the "ex Law 10" report (Fig. **2**).

Figure 2: Termus Bim (source: Acca Software).

It is useful for obtaining permits, selling or renting properties, and accessing government incentives for construction or renovation. The software supports sustainable architecture, which is essential in today's environmentally conscious world. It allows accurate input of building data such as location, geographic orientation, and climate zone. Users can create the building envelope's layer structure using materials from an extensive library or custom-made ones (Fig. **3**). Windows and systems can also be selected from the library or customized with manufacturer data. Once all data is entered, the software calculates energy demand in kWh/m². It assigns an energy class and suggests improvements where needed.

The final goal is NZEB certification, required to obtain construction permits for new buildings.

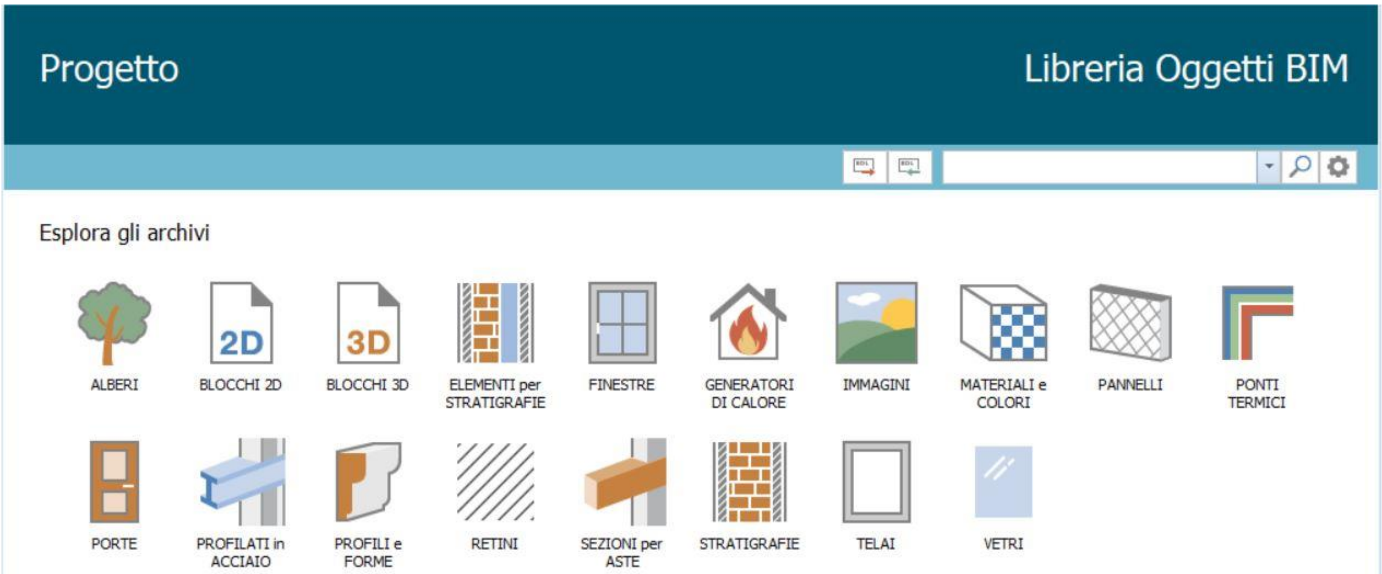


Figure 3: BIM object library (Source: Termus BIM).

3.2. Methodology

The methodological framework was developed taking into account the following articulation:

1st Phase: identification of the scope of emission assessment: operational phase (module B) and production phase (A1, A2, A3)

2nd Phase: identification of the technological system being modeled: passive building systems (envelope, roof, intermediate floor slab, basement slab)

3th Phase: identification of the case study: building with a dry construction system, structural steel load-bearing structure, designed in compliance with the parameters of the LEED Platinum protocol

4th Phase: estimation of emissions in the operational phase (module B): modeling with energy performance software through gap-analysis, in order to identify any critical design issues

5th Phase: estimation of emissions in embedded phase (modules A1, A2, A3): modeling with excel tool, through application of ICE (inventory Carbon Energy), through gap-analysis, in order to identify any critical design issues

6th Phase: analysis of results

7th Phase: recommendations about the most appropriate design choices, for the purposes in the premises

4. Case Study

The chosen case study is a project that involved the University Campus of Fisciano and concerns the construction of a new building, called C3, intended to house the "Life Science Hub" laboratory and some new offices (Fig. **4**).

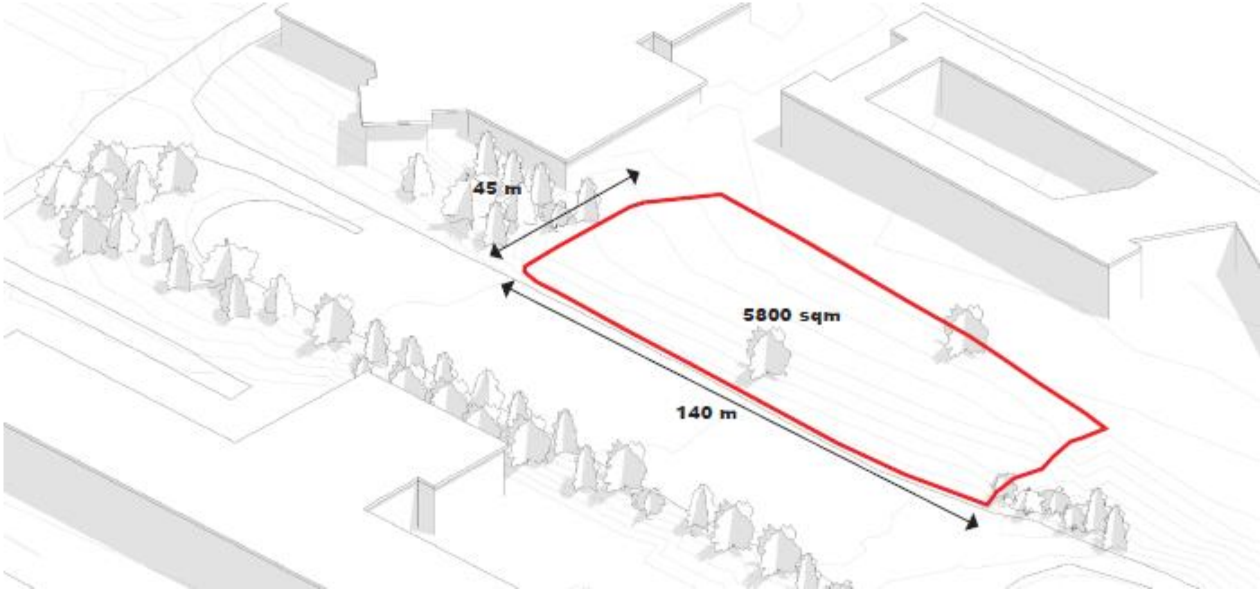


Figure 4: Lot where building C3 will be built (Source: University Technical Office).

It is a rectangular building (14.8 m x 25.4 m) divided into three floors and oriented with the longest sides in the direction from South-West to North-East. The project includes a load-bearing steel structure and an external envelope made with the use of insulated panels integrated with full-height windows (Fig. **5** represents first floor plan).

As for the glazing, these belong to the SCHÜCO AWS 75 SI series with a thermal transmittance of 0.5 W/m²K.

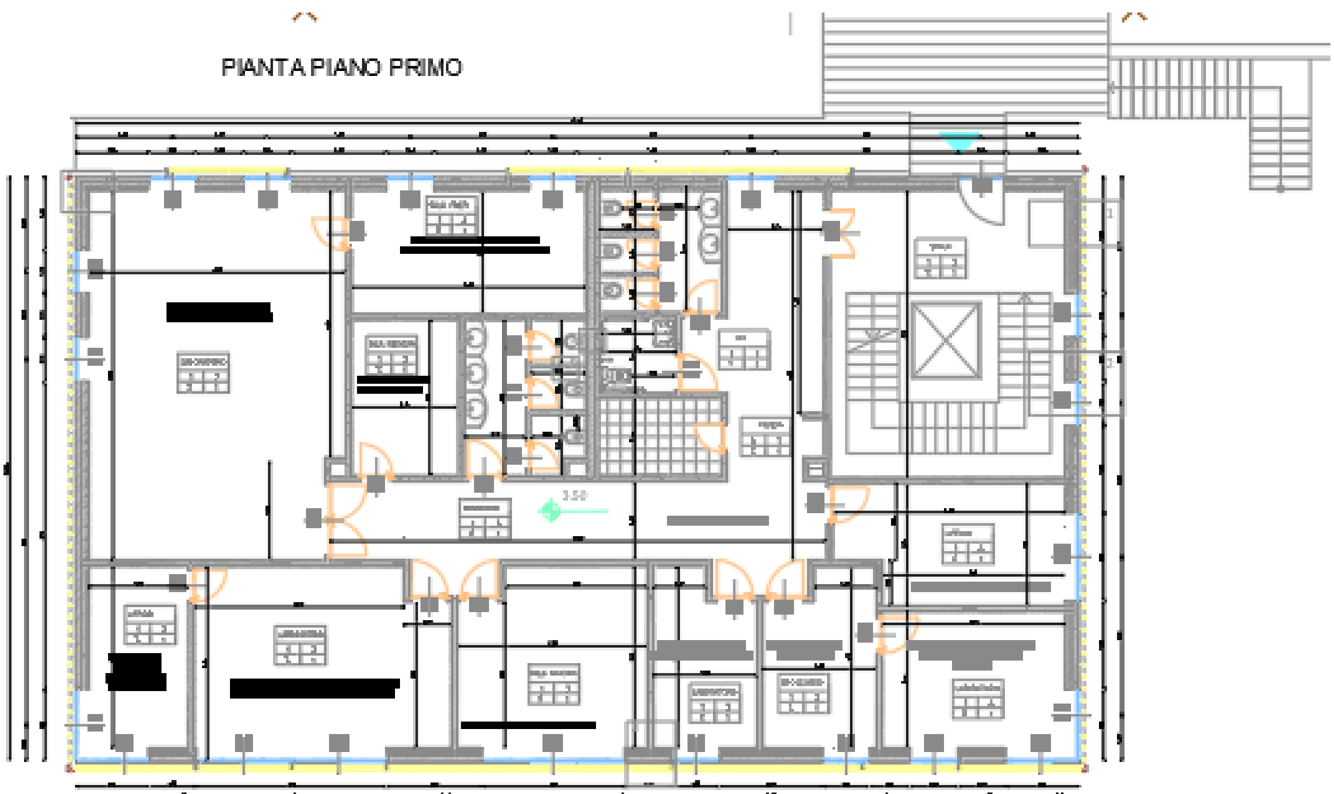


Figure 5: First floor plan (Source: General report of building C3).

One of the main architectural features is certainly the choice to use a system of metal screens that wrap around the entire building. The use of the brise-soleil sunshade aims to protect the facades, and therefore the internal environments, from the sun's rays and the consequent overheating as well as regulating the intake of external light if there are many glass surfaces (Fig. **6**).

Figure 6: South-West facade (Source: General Report).

At the plant level, it was decided to insert two heat pumps, one 44 kW (COP 3.8 – EER 3.5), the other 121 kW (COP 3.8 – EER 3.5) for heating and cooling. For the production of domestic hot water, instead, a 3.8 kW heat pump (COP 11.05) was inserted. There is also a mechanical ventilation system and a photovoltaic system with a power of 95 kW.

All these features have brought the building into the highest energy class as well as having it classified as NZEB.

The chosen building has a steel load-bearing structure. The choice, in fact, was not random but dictated by the fundamental role that this material plays in helping the construction sector with the objectives of the European Green Deal.

Steel is a resistant and durable material (Fig. **7**), flexible and adaptable and these properties allow it to be used in the creation of ambitious, innovative projects with a particularly valuable architectural value. But the fundamental aspects for sustainable architecture concern its recycling capabilities (it is 100% recyclable) and reuse once it has reached the end of its life. In fact, the materials used for a steel structure can be recovered and reused several times for other projects, leading to a reduction in the overall environmental impact of construction activities. Furthermore, the production process is less polluting than the processes carried out for other materials, such as cement, thanks to the introduction of electric arc furnaces which, compared to the old furnaces used, guarantee a limitation of noise, reduction of dust, a 50% reduction in the need for water and energy used and a significant limitation of CO_2 emissions.

In the world, 14 tons of steel are recycled every second, thus avoiding further consumption of oil for the production of materials as well as reducing the environmental burden, CO_2 emissions and other pollutants.

Figure 7: Steel load-bearing structure.

4.1. Operational Emissions Mitigation Hypothesis

Pursuant to Legislative Decree 199/21 [19], from June 2022, newly constructed private buildings and all buildings undergoing significant renovation must be designed to provide for the installation of systems powered by renewable sources, so as to cover 60% of the energy consumption expected for the production of domestic hot water and 60% of the energy consumption expected for summer and winter air conditioning.

To calculate the power that the system will need, you can use a simple formula that allows you to obtain the electrical power expressed in kW:

$$P = \frac{1}{K} * S$$

Where S indicates the floor area of the building expressed in m².

In the case of building C3, since the surface area is 390 m², the electrical power limit is 21.45 kW, while the designed system, as already seen, will be 95 kW. Therefore, the percentage of coverage by energy produced by the system powered by renewable sources is:

- For domestic hot water equal to 99.93%.
- For domestic hot water, winter air conditioning, summer air conditioning 61.06%.

As a result, it falls well within the legal limits.

- Fixtures

The planned fixtures already have very high-performance features that contribute to protecting the internal environments from the outside while maintaining the optimal internal temperature. Despite this, it is still possible to improve the thermal performance of the entire building by thinking of looking for fixtures with an even more advantageous thermal transmittance than that belonging to the fixtures Schüco. For example, you could opt for some double-glazed glass products from the Pressglass company, which, among other alternatives, offers products with a thermal transmittance of 0.4 W/m²K [20]. The forecast of higher performing fixtures (compared to the design choice) did not register significant improvements.

Table 1: Replacement of window frames.

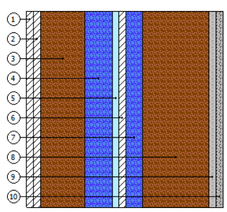
Replacement of Window Frames		
	Eph, nd kWh/m² Year	**Epc, nd kWh/m² Year**
Royal building	7,3113	16,9945
Hypothesis 0	6,4324	17,2152

From these data (Table **1**) it is possible to deduce that a reduction in the thermal transmittance of the windows translates into a notable benefit in the winter period, in the first part of the graph a reduction in the Eph index is noted, nd. This does not guarantee an equal benefit in the requirement for air conditioning in the summer period, in fact, it is possible to note a worsening, albeit minimal, of the Epc index, nd.

- Opaque Elements

As for the window frames, also for the opaque elements, high-performance materials were used, some of which already embrace the principles of Ecodesign. In the stratigraphy of the external walls and floors, in fact, there are rock wool slabs. The stratigraphy with the relative data is shown below (Tables **2**-**5**).

Table 2: Envelope stratigraphy.

		**Envelope**					
N	**Description from the Inside Out**	**Thickness [cm]**	**Λ [W/mK]**	**C [W/m²K]**	**Δ [kg/m³]**	**δp x 1012 [kg/msPa]**	**R [m²K/W]**
1	Knauf GKB	1.3		16,000	660	19	0.063
2	Knauf GKB	1.3		16,000	660	19	0.063
3	Natureboard Silence 80 mm	8.0		0.425	70	193	2,353
4	Air gap horizontal flow 50 mm	5.0		5,423	1	193	0.184
5	Knauf Diamond	1.3		20,000	1.000	19	0.050
6	Knauf GKB with vapour barrier	1.3		16,000	680	0	0.063
7	Air gap horizontal flow 30 mm	3.0		5,423	1	193	0.184
8	Natureboard Silence 120 mm	12.0		0.283	70	193	3,534
9	Smoothing Adhesive for Coat SM700	1.3	0.540		1.400	18	0.023
10	Knauf Aquapanel Cement Board Outdoor	1.3		28,000	1.150	3	0.036
Total thickness		**35.5**					

From the analysis of the performance characteristics foreseen in the project, the building is already very high-performance, with excellent thermal behaviour both in winter and summer.

In the stratigraphies shown, rock wool is used as an insulating material and it is precisely on this panel that it is possible to act to seek an improvement in the thermal performance of the casing that is always similar to the principles of Ecodesign. Specifically, the product chosen and used is the Natur Board Silence slab, a rigid panel in rock mineral wool.

Table 3: Inter-floor slab stratigraphy.

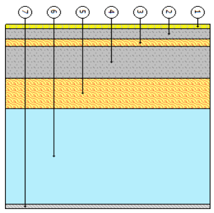
		Inter-floor Slab					
N	**Description from Top to Bottom**	**Thickness [cm]**	**Λ [W/mK]**	**C [W/m²K]**	**Δ [kg/m³]**	**δp x 1012 [kg/msPa]**	**R [m²K/W]**
1	Internal flooring - stoneware	2.0	1,470		1.700	28	0.014
2	Lightweight concrete screed (1600 kg/m³)	4.3	1,080		1.600	2	0.040
3	Rock wool panel	3.0	0.035		100	193	0.857
4	Concrete (1800 kg/m³) - Medium density	13.5	1,150		1.800	2	0.117
5	Rock wool panel	12.5	0.035		100	193	3,571
6	False ceiling air	40.0		2,127,659	1	193	0,000
7	Plasterboard (700 kg/m³)	2.0		10,000	700	19	0.100
	Total thickness	**77.3**					

Table 4: Base slab stratigraphy.

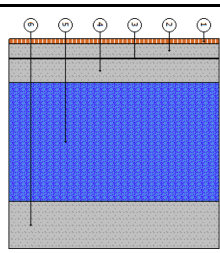
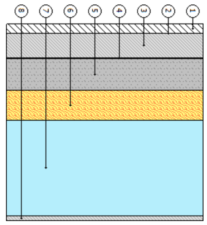
		Base Slab					
N	**Description from Top to Bottom**	**Thickness [cm]**	**Λ [W/mK]**	**C [W/m²K]**	**Δ [kg/m³]**	**δp x 1012 [kg/msPa]**	**R [m²K/W]**
1	External flooring - klinker	2.0	0.700		1,500	28	0.029
2	Lightweight concrete screed (1600 kg/m³)	6.0	1,080		1.600	2	0.056
3	Vapor barrier	0.4	0.500		1.000	0	0.007
4	Concrete (1800 kg/m³) - Medium density	10.0	1,150		1.800	2	0.087
5	Air gap downflow 500 mm	50.0		4,293	1	193	0.233
6	Concrete (2400 kg/m³) - High density	20.0	2,000		2.400	1	0.100
	Total thickness	**88.4**					

Table 5: Roofing stratigraphy.

		Roofing					
N	**Description from Top to Bottom**	**Thickness [cm]**	**Λ [W/mK]**	**C [W/m²K]**	**Δ [kg/m³]**	**δp x 1012 [kg/msPa]**	**R [m²K/W]**
1	Concrete and gravel ("washed stone")	4.0	0.330		1.200	3	0.121
2	PVC thickness 1.2 mm	0.1	0.150		1.400	0	0.008
3	Lightweight screed with polystyrene (80%)	10.0	0.104		350	3	0.962
4	Vapor barrier	0.4	0.500		1.000	0	0.007
5	Concrete (1800 kg/m³) - Medium density	13.5	1,150		1.800	2	0.117
6	Rock wool panel	12.5	0.035		100	193	3,571
7	False ceiling air	40.0		2,127,659	1	193	0,000
8	Plasterboard (700 kg/m³)	2.0		10,000	700	19	0.100
Total thickness		**82.5**					

- The Comparison Parameters

Alternative hypotheses to rock wool were evaluated: hemp, straw, cellulose and jute. For the purposes of energy modeling, the use of a market product was assumed. The reference parameters for the comparison are:

- thermal conductivity (λ_D)
- thermal transmittance (Yie)
- the thermal performance index useful for heating (Eph, nd)
- the thermal performance index useful for cooling (Epc, nd)

The indices quantify the useful thermal energy requirement of the envelope in the winter or summer period. Their values depend on the building's contribution-dispersion ratio.

- Hypothesis 1: Hemp

A technology that is increasingly finding space in green building is hemp, a renewable raw material. Among its advantages, we must certainly consider the low impact it has on the environment, a good thermal insulation capacity, the ability to absorb carbon emissions, which is a notable feature always keeping in mind the objectives of the European Green Deal. Finally, its production process is simplified and cheaper, thanks to the smaller number of materials and layers.

However, there are some that we can define as its disadvantages, the main limit of hemp concerns its low load capacity, in fact it is a highly aerated material that compresses excessively if loaded. Consequently, it is possible to use hemp as a load-bearing element only if the addition of sand is foreseen, in this case, however, its thermal performance decreases.

For this first hypothesis, I chose a hemp fiber panel with a density of 100 kg/m³, produced by Edilcanapa. The insulating panel in question is identified as Canapannel 100.

Canapannel 100 can be used for external insulation, roof insulation and as cavity insulation and is suitable for both new buildings and for renovations or thermal and acoustic corrections of existing environments. Other features include the ability to reduce mold and condensation, thanks to its high breathability, and the ability to accumulate heat and humidity, redistributing it evenly. Obviously, at the end of its life cycle it can be reused for all the applications already indicated [21].

Canapannel 100 can be produced with different thicknesses, this allowed me to easily choose the panel with the right thickness to replace the previous Naturboard Silence panel in the stratigraphies of the vertical and horizontal elements on the Termus BIM software (Fig. **8**).

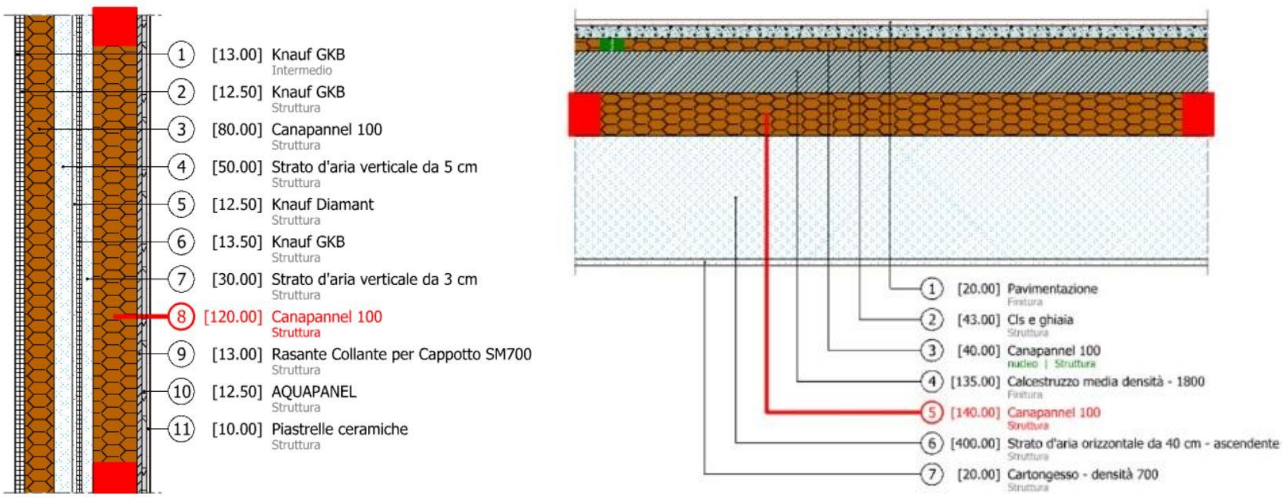


Figure 8: Stratigraphy with use of the hemp panel, for the vertical (left) and horizontal (right) opaque elements.

At this point, after having corrected the thermal bridges thanks to the specific command already proposed by the software, it is possible to carry out the checks required by law and extrapolate the Tables containing various relevant information, for example the energy class which, as we can see in Fig. (**5**), is always the highest (A4). Furthermore, the building continues to be certified as a nearly zero-energy building (NZEB), a fundamental requirement as it is a new construction.

Table **6** shows the thermal conductivity and transmittance values of hypothesis 0 (rock wool) and hypothesis 1 (hemp). It is immediately evident that, even though there is a more unfavorable conductivity in hypothesis 1, the thermal transmittance of the envelope appears almost unchanged. A different situation is found in the thermal performance indices: from Table **6** it is possible to note that the behaviour of the envelope, in the winter period, is more disadvantageous in hypothesis 1. The same argument also applies to the behaviour of the building during the summer period.

Therefore, the use of hemp panels, specifically the Canapannel 100 panel, while maintaining all the initial dimensions, has not brought any improvement to the building. It should be noted, however, that the building is still classified as NZEB with energy class A4 and always has excellent energy and thermal performance.

Table 6: Energy data Building C3 (Hypothesis 1).

Hypothesis 1: Hemp				
	λD W/mK	Yie W/m²K	Eph, nd kWh/m² Year	Epc, nd kWh/m² Year
Hypothesis 1	0.039	0.024	6,5348	17,2638
Hypothesis 0	0.034	0.0241	6,4324	17,2152

- Hypothesis 2: Cellulose

For the second hypothesis I considered a cellulose fiber panel, called Vital, a thermal and acoustic insulator distributed by the company Celenit [22]. It is an innovative product for long-lasting insulation solutions, healthy and that contribute to improving the comfort of indoor environments, above all it is a material made from renewable natural resources, namely wood. The production processes of these panels are environmentally responsible since the cellulose production process produces more energy than it consumes. From one cubic meter of wood 10 cubic meters of insulation are produced, furthermore all the materials used during production can be recycled in the process.

Vital panels are excellent thermal and acoustic insulators, stabilize variations in air humidity in closed environments, prevent the formation of mold, bacteria and fungi and are not corrosive. Finally, it complies with the UNI EN 13171 standard [23]. Also in this case, different thicknesses are available, including those used in the stratigraphy. For the missing ones, instead, I opted for a union of two panels whose sum would reach the desired thickness (Fig. **9**).

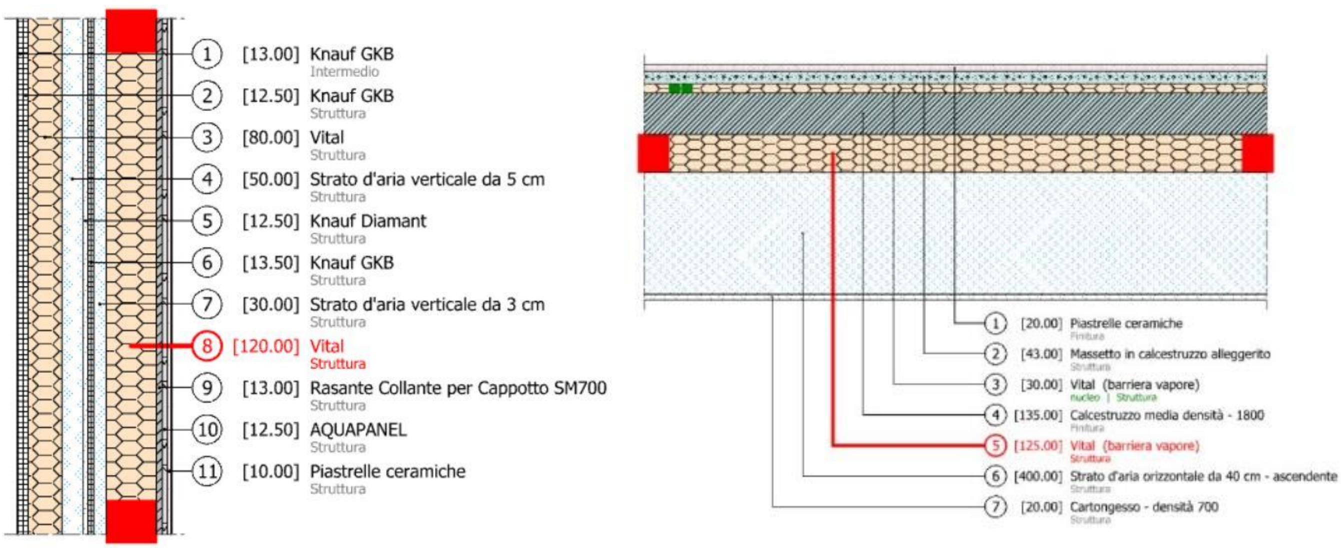


Figure 9: Stratigraphy with cellulose panel for the vertical (left) and horizontal (right) opaque elements.

In this case too, I first resolved the thermal bridges, after which I carried out the legal checks and then extrapolated Table **6**. This is the procedure I carried out for all four hypotheses. With hypothesis 2, a worsening of the thermal conductivity also translates into a worsening of the thermal transmittance of the building envelope.

Table 7: Energy data Building C3 (Hypothesis 2).

Hypothesis 2: Cellulose				
	λD W/mK	Yie W/m²K	Eph, nd kWh/m² Year	Epc, nd kWh/m² Year
Hypothesis 2	0.037	0.0298	7,2305	17,149
Hypothesis 0	0.034	0.0241	6,4324	17,2152

All this also leads to lower performance of the envelope both during the winter and summer periods, as can be seen from the thermal index values in Table **7**. So even with this second hypothesis I do not see improvements, however the building continues to have the NZEB classification and continues to enjoy the highest energy class, in addition to still recording excellent energy and thermal performance.

- Hypothesis 3: Straw

The third hypothesis involves the use of semi-rigid insulating panels made of rice straw called RH50, produced by Ricehous srl SB. It is a panel composed of 92% rice straw fibers, joined together by 8% thermofusible polyester fibers that form a semi-rigid insulating mat. This is a valid product both for new constructions and for thermal and hygrometric renovations of existing buildings. As regards durability, this vegetal fiber, which also has a low carbon content, is extremely resistant to deterioration [24].

These panels can be produced with different thicknesses, from a minimum thickness of 45 mm to a maximum of 200 mm. As for the previous hypotheses, I am going to act on the stratigraphies to insert the chosen panel (Fig. **10**).

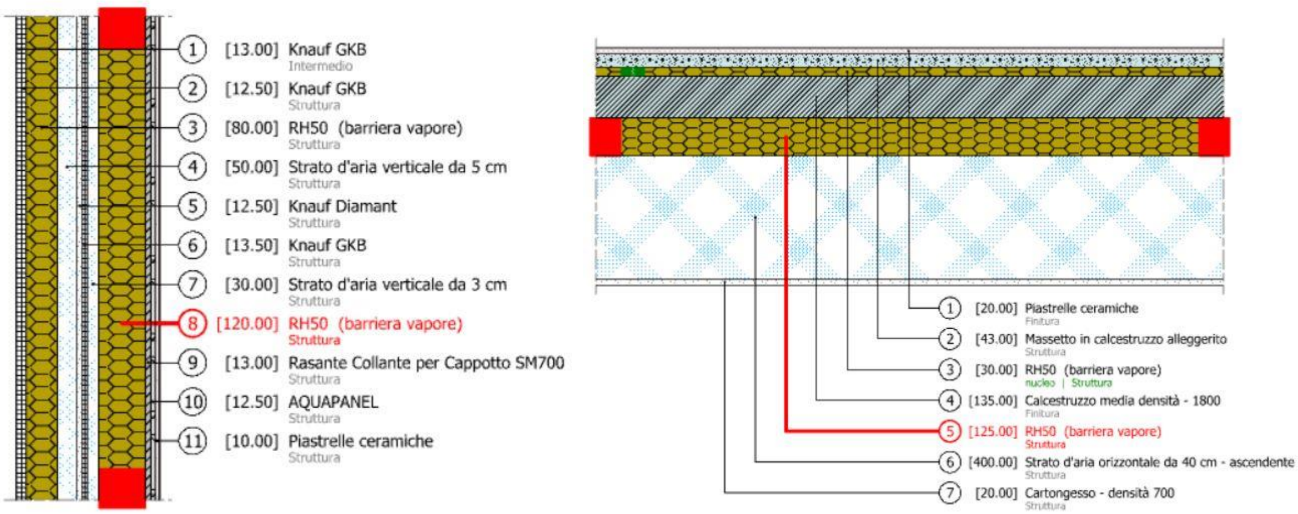


Figure 10: Stratigraphy with rice straw panel, for the vertical (left) and horizontal (right) opaque elements.

This hypothesis involves a clear worsening compared to the two previous ones. As can be clearly seen in Table **8**, the characteristics of the chosen panel, including a higher thermal conductivity than that of rock wool, have led to a significant increase in the thermal transmittance of the envelope. This has led to a significant change in the thermal behavior of the building:

Table 8: Energy data Building C3 (Hypothesis 3).

Hypothesis 3: Straw				
	λD W/mK	Yie W/m²K	Eph, nd kWh/m² Year	Epc, nd kWh/m² Year
Hypothesis 3	0.039	0.0283	7,7573	16,8058
Hypothesis 0	0.034	0.0241	6,4324	17,2152

In fact, the building envelope records a worsening for both thermal performance indices, but while the index referring to the summer period continues to satisfy the legal checks being always lower than the value of the reference building, for the winter period it is not possible to say the same. In addition to the worsening recorded compared to hypothesis 0, in fact, the calculated Eph, nd value is slightly higher than the value with respect to the reference building leading to the failure of the check:

Table 9: Thermal performance indices.

EPh,nd	Thermal performance index useful for heating	kWh/m²year	7,7573
EPh,nd_Lim	Thermal performance index LIMIT for heating	kWh/m²year	7,5394

Consequently, although the Termus software always shows that the building has the highest energy class, it is no longer classified as NZEB. Furthermore, in Table **9** note a change in the energy performance of the building, which continues to have excellent behavior during the summer period, but then records a worsening during the winter period.

- Hypothesis 4: Jute

For this last hypothesis I have planned the use of insulating panels made of recycled jute fiber (such as old discarded cocoa and coffee sacks) fixed three-dimensionally with bicomponent PET fibers. These are products used for insulation of walls, roofs, attics, false ceilings and false walls, ecological and free of harmful and polluting substances. Jute is a highly breathable material and resistant to humidity and mold as well as being completely recyclable [25].

The chosen product is the Jutaton D32 panel, produced by Ton Gruppe and also in this case different thicknesses are available which allowed the previous product to be easily replaced (Fig. **11**).

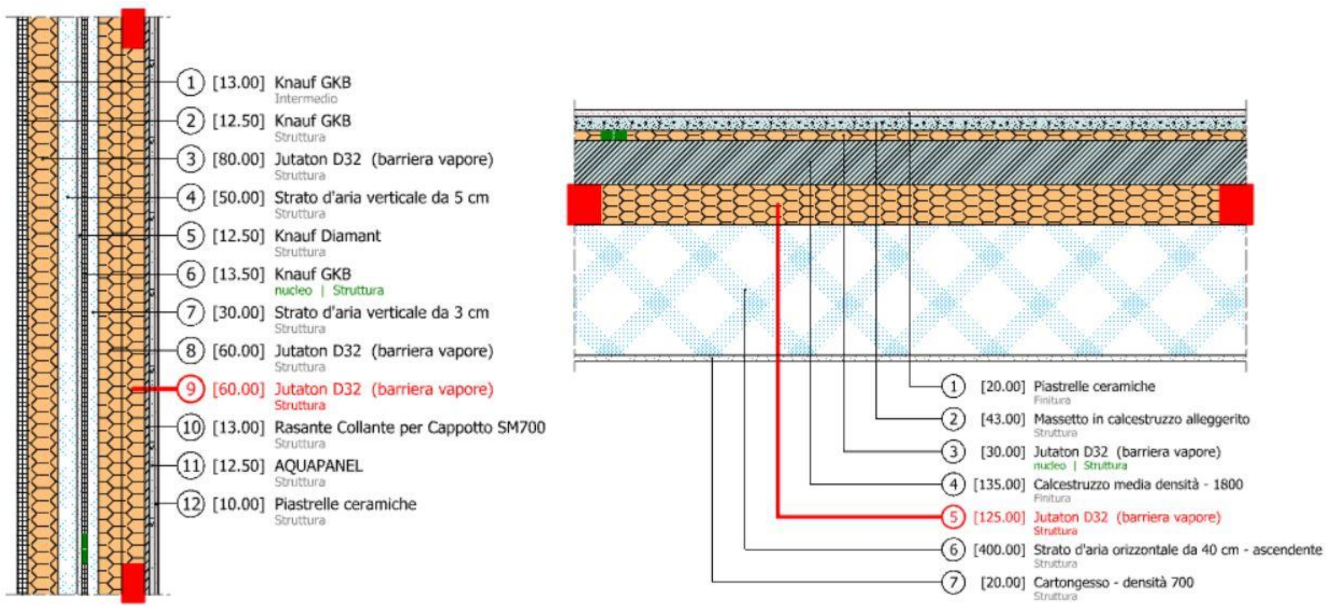


Figure 11: Vertical stratigraphy with jute panel, for vertical (left) and horizontal (right) opaque elements.

In this case I also extrapolate the values calculated using the software. This last hypothesis highlights a higher value of the thermal transmittance of the envelope compared to the value calculated for hypothesis 0.

Table 10: Energy data Building C3 (Hypothesis 4).

Hypothesis 4: Jute				
	λD W/mK	Yie W/m²K	Eph, nd kWh/m² Year	Epc, nd kWh/m² Year
Hypothesis 4	0.0369	0.027	7,0526	17,2295
Hypothesis 0	0.034	0.0241	6,4324	17,2152

As for the thermal performance indices, the software has returned again higher values than the values obtained with the rock wool panel, despite this, the indices in question still pass the legal checks (Table **10**). As for the energy class, once again we have the A4 class, furthermore this hypothesis also gives us a building with almost zero energy. In Fig. (**11**) it is also possible to see that the software certifies the excellent energy performance of the building both in the winter and summer periods.

5. Results and Discussions

The results (Table **11**) show that the use of eco-sustainable materials, other than rock wool panels, did not bring significant improvements in the thermal behaviour of the building envelope (Fig. **8**-**11**).

Table 11: The results obtained from the four simulations.

N	Hypothesis	Thermal Conductivity	Periodic Thermal Transmittance	Thermal Performance Index Useful for Heating	Thermal Performance Index Useful for Cooling
		λD W/mK	Yie W/m²K	Eph, nd kWh/m² Year	Epc, nd kWh/m² Year
1	Hemp	0.039	0.024	6,5348	17,2638
2	Cellulose	0.037	0.0298	7,2305	17,149
3	Straw	0.039	0.0283	7,7573	16,8058
4	Jute	0.0369	0.027	7,0526	17,2295
5	Rock wool	0.034	0.0241	6,4324	17,2152

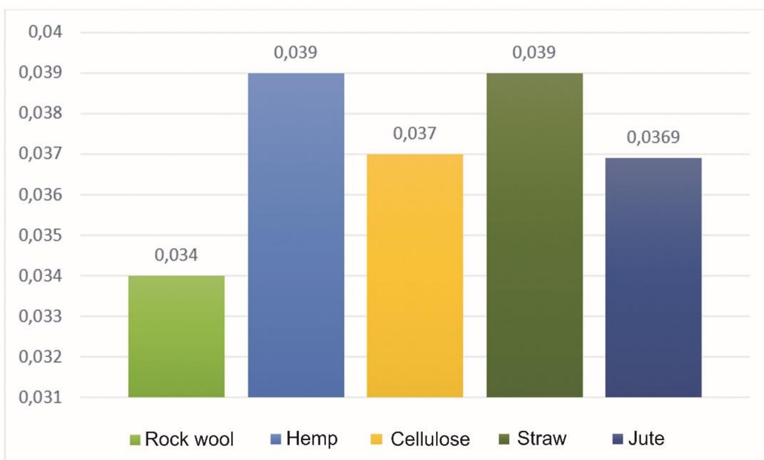


Figure 12: Thermal conductivity graph.

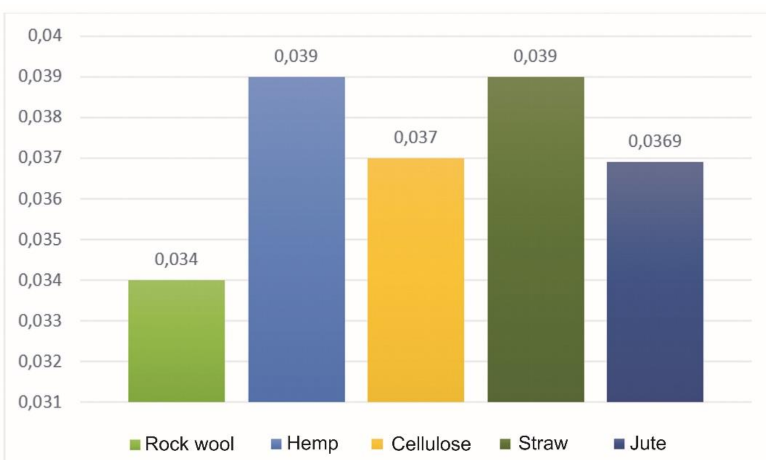


Figure 13: Thermal transmittance graph.

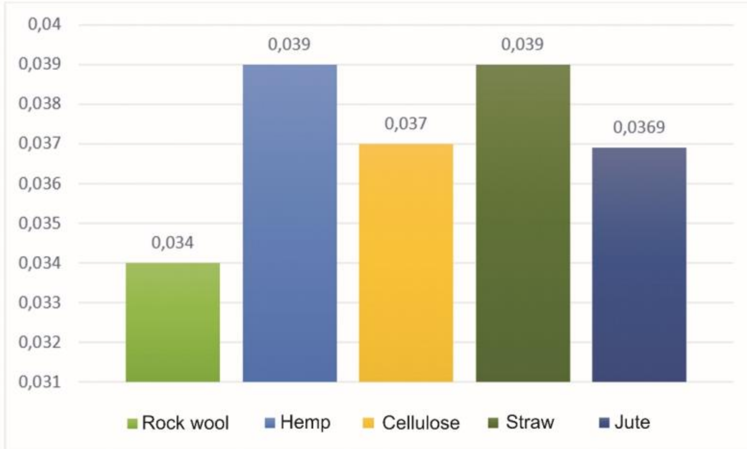


Figure 14: Thermal performance index useful for heating.

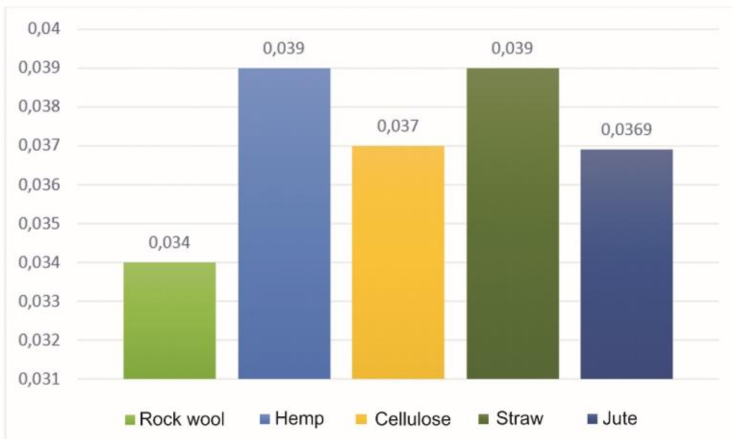


Figure 15: Thermal performance index useful for cooling.

The graphs represented in the Fig. (**12**-**15**), show results related, respectively: Thermal conductivity (Fig. **12**), Thermal transmittance (Fig. **13**), Thermal performance index useful for heating (Fig. **14**), Thermal performance index useful for cooling (Fig. **15**).

Considering these last two graphs, a more homogeneous result, that is, a more advantageous behavior both in the summer and in the winter period, is always given by the choice that includes the use of the rock wool panel.

In fact, for heating it is possible to note that rock wool allows the envelope to return the lowest result among the various hypotheses, synonymous with a more advantageous response in the winter period by the building envelope. It could also be added that among the hypotheses carried out, only hemp, also in this case, could be considered an interesting choice based on the results recorded. As for cooling, however, a completely reversed situation is noted. In this case, hypothesis 3 and hypothesis 4 could make us change our minds about the previous considerations. But why have straw and cellulose panels returned such advantageous results?

It should be noted that if for the cold all insulators are more or less equivalent, for the heat this does not happen and the good evaluation of the material comes into play. To have good summer insulation you need a high thermal inertia. With a material with an optimal thermal inertia I can also have good phase shift values, that is the time that the heat takes to pass from the outside to the inside of the wall. Natural insulators, such as hemp, straw and cellulose, have the ability to absorb, retain and release heat before it enters the house. Another aspect to consider is also the correct evaluation of the thickness of the insulation.

A thickness studied ad hoc for each of the hypothesized materials, would certainly have returned completely different results and perhaps more advantageous than hypothesis 0. But this, obviously, would have entailed changing the layout of the entire structure, which was not intended to be the subject of this study. Focusing on the behavior of the hypothesis that involves the use of straw panels, the latter are able to insulate well from the summer heat precisely thanks to their fibrous composition characterized by empty cavities [26]. In addition to this, other characteristics of different materials probably also come into play, including mass density and hygroscopicity.

5.1. Embodied Emissions Mitigation Hypothesis

The previous evaluation carried out using the Termus software and an evaluation taking into account some fundamental parameters for the thermal behavior of the building, highlighted how the initial project presented characteristics that made it already very high-performing in terms of thermal and energy performance. We also saw how the materials chosen are well evaluated considering the principles of Ecodesign. Thus, since none of the hypotheses generated a result that showed an actual improvement in performance during the project's operation phase, I decided to shift my attention to another phase: the production phase of the materials previously analyzed and hypothesized. As already mentioned, the European Union aims to make our continent climate neutral by 2050. Each phase of construction of a building has an impact on the environment, consequently the impact on carbon emissions is also to be considered an important aspect to evaluate when making construction choices. Specifically, I will calculate the total CO_2 emissions generated by the production activity (which in the life cycle of a building or a product in general is phase A1-A3) of the materials of interest: rock wool, hemp, cellulose, straw and jute. The first step concerns the calculation of the weight with respect to the elements of interest, therefore the insulation, present throughout the building. To help me with the calculation I once again relied on the Termus software thanks to which I was able to extrapolate some fundamental data about the dimensions of the plant and the heights, which I then collected in Tables **12** (**a**-**b**). At this point, I considered the total thickness of the insulation present in the stratigraphy of the entire envelope and multiplied it by the area of the facades obtaining the total volume of the insulation.

Table 12a: Dimensions of Building C3.

	Perimeter (m)	Height (m)	Area (m²)
First floor	68	3.5	238
Second floor	131,169	7.7	1010,0013
Third floor	131,169	12	1574,028

I repeated the same operation for the floors, obtaining the total volume of the insulation in the horizontal elements.

Table 12b: Dimensions of Building C3.

	Attic cm²	Floor Insulation Thickness (cm)	Insulating Volume (cm³)
First floor	13116,9	20	262338
Second floor	13116,9	21	275454,9
Third floor	13116,9	22	288571,8
Coverage	13116,9	12.5	163961,25

Once I knew the total volume for the horizontal and vertical elements, with a simple sum I obtained the total volume of the entire insulation present in the entire structure (Table **13**). I later converted the result obtained intom², so as to give me an advantage when using the following formula.

Table 13: Volume of insulation in Building C3.

Insulating Volume (cm^3)	Total (cm^3)
368900	5364471,365
1565502,015	
2439743,4	Total (m^2)
262338	5,364471365
275454,9	
288571,8	
163961,25	

To calculate the carbon emissions, I also need to know the weight in kg of the individual materials assumed in the entire envelope. So I consider the specific weight of each of them and multiply it by the total volume:

Table 14: Weight calculation.

Material	Specific Weight (kg/m^3)	Volume (m^3)	Weight (kg)
Rock wool	70	5,364471365	375,5129956
Hemp	100	5,364471365	536,4471365
Cellulose	30	5,364471365	160,934141
Straw	50	5,364471365	268,2235683
Jute	32	5,364471365	171,6630837

Knowing the weight of each material, I can deal with the second unknown, in fact the calculation to know the incorporated carbon is possible by associating each material with the Embodied Carbon coefficient of the material itself which is present in the ICE (Inventory of Carbon and Energy) database [27], as shown in Table **14**.

Embodied Carbon represents all the carbon emissions caused by a product that are not directly linked to its use. It is a coefficient that allows us to make a more complete analysis in order to correctly evaluate whether a building, with "zero" emissions, is actually less impactful than a similar one but with some less efficient properties [28].

Having identified the different coefficients (Table **15**), I can move on to using the formula with which I will calculate the total carbon emissions generated by the production activity:

$$\mathrm{CO}_{2\mathrm{A1-A3\,(i)}}\,[\mathrm{kgCO}_{2\mathrm{e}}] = \mathrm{P}_{(\mathrm{i})}[\mathrm{kg}]\ \mathrm{x}\ \mathrm{EC}_{\mathrm{ICE\,(i)}}[\mathrm{kgCO}_{2\mathrm{e}}/\mathrm{kg}]$$

Table 15: Embodied Carbon calculation.

Material	Embodied Carbon $kgCO_2e/kg$	Weight (kg)	CO_2 $kgCO_2e$
Rock wool	1.12	375,5129956	420,57
Hemp	0.138	536,4471365	74.03
Cellulose	0.005	160,934141	0.80
Straw	0.01	268,2235683	2.68
Jute	0.234	171,6630837	40,17

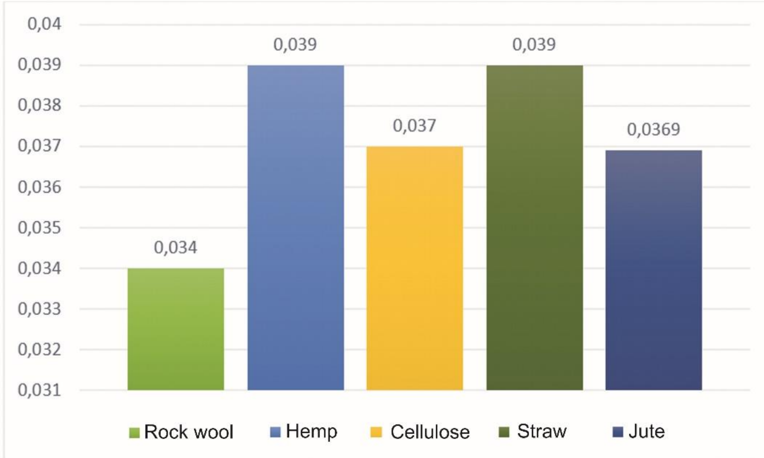


Figure 16: Graph representing CO_2e emissions (in $kgCO_2e$ per functional unit), relative to each material considered.

Therefore, it is possible to state that, among the four hypotheses, in addition to the initial hypothesis, the cellulose panel is the one that presents the lowest CO_2 emissions during the production phase. Unlike the results obtained previously, in this case the most disadvantageous result was given by the rock wool panel. Obviously, these are results obtained in relation to the dimensions and quantity used in this specific project and without making any changes to the initial dimensions (Fig. **16**).

6. Conclusions

The aim of the study is to achieve an improvement in the energy performance (operational and embodied) of the envelope of a building with a steel construction system. From the initial data, the building presented excellent performances both in terms of heat and energy, having been designed according to NZEB parameters. The envelope presented an optimal thermal behavior, both in summer and winter. Slight but not significant improvements were obtained by intervening on the transparent wall, through the replacement of the window frames.

We then intervened on the opaque wall, verifying possible benefits in function of possible alternatives of thermal insulation. The alternatives considered (hemp, cellulose, jute) although proving to be performing, did not register significant discrepancies compared to the project material (rock wool).

The second phase of the study concerned the possibility of reducing the carbon footprint in the production stage (A1-A3). In this context, the material planned in the project for thermal insulation, rock wool, proved to be the most impactful in terms of emissions. It was in fact found that the insulating alternatives considered presented lower impacts in terms of carbon footprint.

The study highlights an integrated assessment of the operational and embedded impact of the thermal insulation of the envelope. The insulating material of the project (rock wool), although proving to be high-performing in terms of consumption containment in the operational phase, proves to be less effective in terms of carbon footprint, in a “cradle to gate” LCA assessment. The methodology, together with the tools used, can offer insights for practitioners to achieve reward scores in the preparation of the MEAO of procurements (Most Economically Advantageous Offer).

The research focuses on the climate context of southern Italy and, from a regulatory perspective, refers to Italian national standards.

Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Funding

The authors declare that this research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

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