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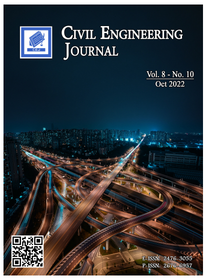


# A Highly Sustainable Timber-Cork Modular System for Lightweight Temporary Housing

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**Abstract**

In recent years, global society has been subjected to great change due to unpredictable events such as pandemics, migrant flow, urban homeless, wars, and natural disasters. There has been an increased demand for fast and easily constructed buildings characterized by limited space and used for a limited time, modular and flexible self-assembly homes that are reusable without compromising comfort and environmental sustainability. A highly sustainable timber-cork modular system for lightweight temporary housing (LTH) is proposed in this paper. The structure of the proposed LTH was designed as a succession of modular timber portal frames composed of spruce boards hinged together. The concept of the prototype was a full modular shelter. It was possible to interchange every piece of the building, the structural elements, and the walls with each other. Due to the modularity of the elements of which the shelter was composed, this system could offer different solutions to the events above. The proposed LTH was analyzed in terms of its structural, thermal, and environmental performance. The structural system is very reminiscent of the platform frame, characterized by a light load-bearing frame consisting of solid timber uprights and crosspieces connected to the internal frame by means of a mechanical connection. The structural FEM analysis highlighted the structure's capacity to withstand wind with a velocity of 72 $m \cdot s^{-1}$, corresponding to the F3 of the enhanced Fujita Scale (EF Scale) of tornado damage intensity. The thermal analysis highlighted a yearly energy use of 430.49 kWh to maintain a set-point temperature indoors of 20-26°C compared with a yearly energy use of 625.93 kWh for a common container house (CH) with the same dimensions under the same environmental conditions. Finally, a Life Cycle Analysis comparison between the proposed LTH and the CH was carried out by means of the One Click LCA software. Two different scenarios of service life were considered: one of 10 years and the other of 5 years. The results highlighted the higher sustainability of the proposed LTH than that of the CH for the required service life (Req SL) period. In particular, the calculated greenhouse gas emissions of the LTH (3.52ž $10^3$ $kgCO_2$ eq) were less than 1/2 of the gas emissions of the CH (8.53ž $10^3$) for a Req SL of 10 years and about 1/3 for a Req SL of 5 years. Furthermore, the LTH showed a value of biogenic carbon storage (7.76E2 $kgCO_2$) about 6 times bigger than the temporary house container (1.31E2 $kgCO_2$).

*Keywords:* Natural Materials; Sustainability; Self-Built Shelter; Disaster Relief; Wood Constructions; Emergency Shelter; Rural Tourism.

## 1. Introduction

In the last years, humanity has been subjected to great transformations due to global events such as pandemics, migrant flows, resource depletion, poverty increases, wars, and natural disasters. These occurrences have brought about the necessity of designing new houses and dwellings to meet new user needs. In particular, there has been an increased demand for fast and easy buildings characterized by limited space, use for a limited time, modularity and flexibility, self-assembly homes, and reusability without compromising comfort and environmental sustainability.

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Social distancing and isolation procedures have been enforced to contrast the transmission of COVID-19 [1], because the quarantine is very important to limit the spread of the virus. More recently, the migrant flows and refugees from war zones have become a new critical issue for governments to deal with [2-4]. In this context, providing new temporary accommodation to limit social contact or protect and house vulnerable people has become a critical issue for public administrations. New dwellings, such as Lightweight Temporary Housing (LTH) are necessary. In the past, this type of building was used exclusively for emergencies or disasters. Over the past few years, the LTH has become more than just an opportunity to create disaster relief shelter but a resource for the building sector and for the public administrations, because it offers a fast solution to make low cost and multifunctional dwelling spaces. Clearly, an emergency shelter and a house have different purposes. Houses include daily household functions and normal routines. The LTH offers a safe and secure area in which to live for a limited time. In accordance with UN/OCHA/ESB (2006), adequate post disaster shelter is defined as an "*immediate environment for all aspects of family life, providing protection from the elements, secure tenure, personal safety, and access to clean water and sanitation, proximity to places of employment and educational and health care facilities*" [5].

The performance of the LTH is similar to that of a traditional house in terms of comfort, a healthy environment, functionality, and safety. Nowadays, the LTHs are proposed for use in different sectors, such as tourism, agriculture, social assistance, worker accommodations, medical services and for emergencies and refugees. The scientific research has not paid great attention to the sustainable assessment of temporary houses [6]. This lack of attention is due to low intensity occupancy and, above all, to the short life span of the use of the constructions. In the past, this approach could have been tolerable, but today, it is not acceptable anymore [2-4].

The choice of low-embodied energy construction materials and components and the use of montage and dismantling systems are important for the sustainability of these constructions. Furthermore, the inhabitants of these buildings request a high level of comfort, which leads to a high level of energy consumption and high $CO_2$ emissions. The main aim of the European Green Deal initiative is to reduce greenhouse gas emissions and take measures to ensure the sustainability of buildings. The EU aims to be climate neutral by 2050, and the building decarbonization and construction sectors are critical to achieving the Paris Agreement commitment and the United Nations Sustainable Development Goals (SDGs) [7]. A very important aspect when evaluating the LTH's sustainability is the time of use and the life span of the building. Bashawri et al. [8] divided the uses of emergency shelters into seven categories:

- ***Emergency Shelter:*** It is used for some hours or days only to deliver life-saving support after the event.
- ***Temporary Shelter:*** It is used for few weeks following an emergency event.
- ***Temporary Housing:*** It is used for long-term periods, from six months to five years.
- ***Transitional Shelter:*** It is commonly relocated from a temporary location to a permanent site; it is used from many months to a few years.
- ***Progressive Shelter:*** It is used in a semi-permanent way; its structural system is designed to be upgradeable for different use in the future.
- ***Core Shelter/One-Room Shelter:*** It is a permanent, durable and strong, but small, house; yet, it is not intended to be a full permanent house.
- ***Permanent Housing:*** It usually refers to shelter solutions which last many years, and to buildings which last in excess of 10 years. It should be resistant and resilient to future hazards and disasters.

The above-mentioned classification can be applied generally to the LTH.

Containers are the most commonly used type of LTH. For a long time, they were widely used as temporary shelters to help victims of natural disasters and industrial workers involved in large-scale construction. In the past few decades, a lot of research has been developed to improve the comfort level and application scope of container houses. In their study, Zafra et al. [9] they investigated the structural and thermal performance of CH in the hot and humid climates of the typhoon-frequented regions. The study showed that increasing the insulation resistance of the envelope did not improve the indoor thermal comfort.

Nevertheless, a lot of research is oriented to improve the comfort and the safety of the users [10]. People request safe and solid shelter especially in emergency situations, and they want it to fit their needs. A number of investigations are concerned with the temporary buildings, which have to be made quickly, with local resources and in a sustainable manner, and be reusable in accordance with standards and national rules. In the last decade, different studies have highlighted also the importance of the embodied energy and emissions of these buildings type [11, 12]. Alshawawreh et al. [13] examined 24 shelter solutions and evaluated their performance in use against the three pillars of sustainability: environmental, social and economical. In a previous study, Salvalai et al. [14] proposed and analysed the performance of a lightweight flexible building in three possible alternative scenarios. The LTH proposed was an and a lightweight steel structure easily disassembled, with an envelope made of dry layers which allows a personalized design, a serial replicability of the concept ensuring a high thermal level of performance, energy saving and an easy and fast assembling. In their study, Hosseini et al. [15] proposed an Integrated Value Model for Sustainability Assessment (MIVES) included in the DesignBuilder software, which supports the decision-makers to adopt the optimal LTH solutions based on the performance and use required. The materials used for the structure and the envelope have to be reusable to limit the environmental impact of the building waste [16, 17]. Timber is often used for framing, beams, and flooring in housing but it can play an equally important role in temporary structures. The timber structures can often be mounted without any support or heavy tools, thanks to their high strength-to-weight ratio. Wood is widely available as a raw material and has a high level of mechanical strength with a low weight and a good heat insulation performance. The wood-based materials are easily reused and recycled. It is possible to adopt building solutions also with the combination of other materials to enhance the sustainability and the thermal performance of the wood [18, 19]. A highly sustainable timber-cork modular system for lightweight temporary housing is proposed in this paper to respond to recent demand. Previous studies have highlighted that lightweight multilayer panels with a core layer made of low-grade sawn timber produce the best results in structural performance, the best heat insulation performance and the lowest costs for production and maintenance [20, 21]. In order to achieve the same results, we have used a sandwich panel with two external agglomerated cork layers [22] and an internal Phase Change Material layer, to enhance the thermal performance of the LTH's envelope [23]. This study intends to fill the gap of the researches in this building field proposing a high sustainable LTH for a middle and long service life.

The article is structured as follows: section 1 is devoted to the problem statement and to the aims of this paper. In section 2, the proposed LTH is described from a modular and structural point of view. The structural analysis and the thermal performance analysis are described in subsections 2.1 and 2.2; in the same subsections, an energy consumption comparison is also carried out. In subsection 2.3, the LCA method is used to perform a sustainability analysis, and a comparison with a different type of temporary housing is carried out. In section 3, the LCA results are reported and discussed. Section 4 is devoted to the discussions. Finally, in section 5 includes the conclusions and suggestions for potential future research. A schematic representation of the analysis methodology proposed is shown in Figure 1.

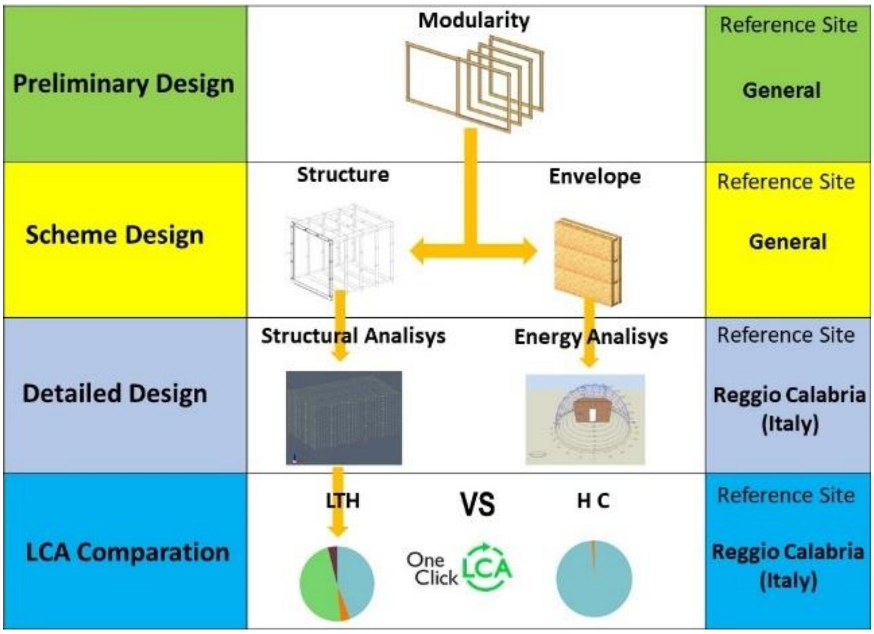



**Figure 1. Stage analysis for a highly sustainable timber-cork modular system for lightweight temporary housing**

## 2. Materials and Methods

The structure of the proposed lightweight temporary house (LTH) was designed as a succession of modular timber portal frames, composed of spruce boards hinged together. They were made of 3-cm thick and 16-cm wide spruce boards with the uprights of the same size as the horizontal beams in the roofing and the floor so it was possible to use timber boards both for the uprights and for the beams. High thermal performance multilayer agglomerated cork panels were assembled for the walls and for the roof of the portal frames.

The concept of the prototype was a full modular shelter. It was possible to interchange every piece of the building, the structural elements and walls with each other. Due to the modularity of the elements of which the shelter was composed, this system could create different solutions. The minor unit, M1, was made of two structural elements, the “portal” [24] and a row of multilayer agglomerated cork panels for the walls and the roof. Through the development of this different module, it is possible to obtain the technological module M2, (Figure 2) or the Housing module M5 and others.

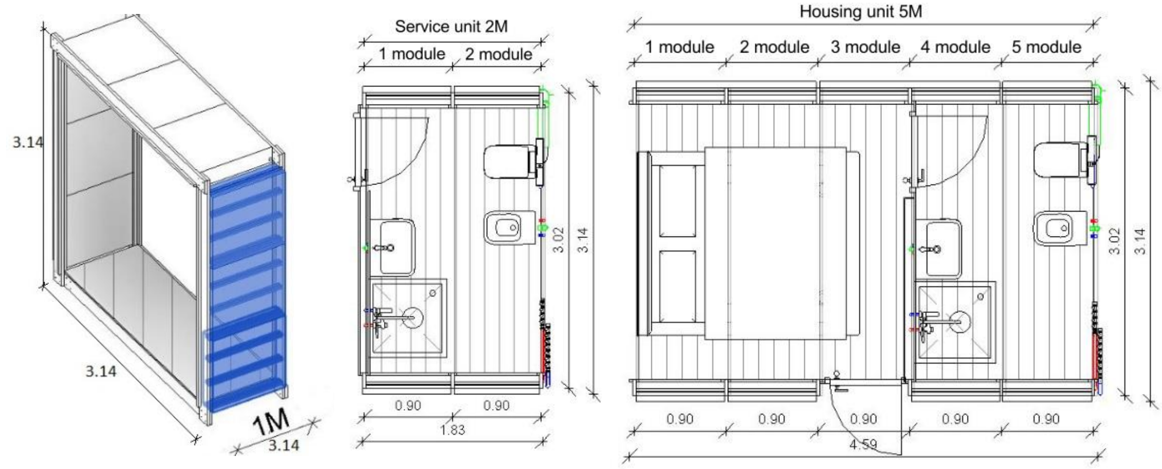
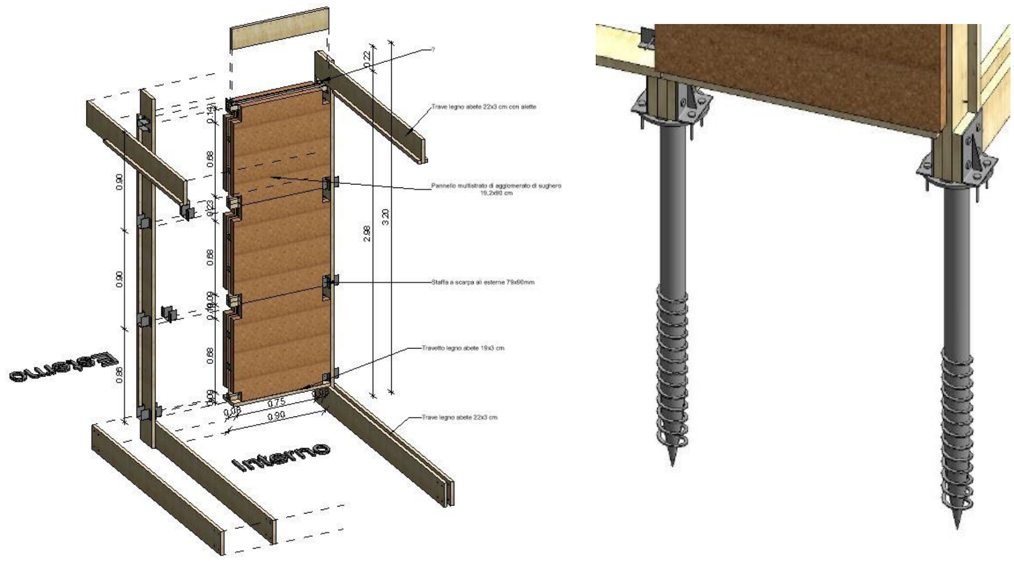



**Figure 2. 3D view of basic module M1, plan view of technological module M1 and Housing Unit M5 (measured in metres)**

The structural system was very reminiscent of the Platform Frame, characterized by a light load-bearing frame consisting of solid timber uprights and crosspieces connected to the internal frame by means of a mechanical connection [25]. The wall elements were manufactured in the factory at different prefabrication levels and assembled on site. This allowed the quick closure of the construction (quick assembly). The walls were made up of multilayer panels, consisting of a horizontal load-bearing framework with an OSB core, which were connected to the uprights of the portals. The external layers of the wall panels were made of 6-cm thick corkboards. A Phase Change Material sheet was installed between the indoor side of the panel and the central OSB layer to control the thermal flux [26].

The structural wall panels that buffered the frame also had the task of preventing instability in the vertical elements. An innovative connection system (steel bracket) was designed in order to join the panels to the upright in a fast and safe way. These connectors create a restraint for the panels, with a variable grade between the pinned and the fixed support. The roof was made using the same principle as the walls but arranged along a horizontal plane. By adapting the design to this grid, it was possible to place the openings in such a way so as not to require the use of additional unnecessary uprights. Each frame was fixed to the ground by means of a couple of screw foundations [27], which created a very practical and quick system to establish a solid base able to support the timber structure and the loads on it (Figure 3).




(a) (b)

**Figure 3. Structural design of the basic module: (a) Shear wall, (b) Screw foundations**

Installation was quick, effective, and precise; it neither produced debris nor required the use of concrete. The system facilitated the construction of the floor plane by correcting unavoidable errors made when inserting the screws into the soil. This foundation did not require the ground to be leveled because a specific leveling system was designed to align the head plate of the screw foundations. Once installed, they were immediately usable and raised the floor above ground level so that the rainwater flowed below the structure. In short, the peculiarities of the LTH structure proposed were:

- Limited technical "expenditure" due to the systematic use of standard wood sections;
- Arrangement of the uprights determined by the dimensions of the wall panels;
- Wall panels assembled in the factory and installed on site;
- The stiffening elements of the building were the walls themselves;
- The foundation did not require the ground to be levelled;
- The LTH assembly was quick with dry connections;
- The LTH could be assembled on site and disassembled after use;
- The structure could withstand strong tornadoes.

### 2.1. Structural Analysis

The structural analysis was carried out by means of SISMICAD; an industrial structural simulation software program based on the Finite Element Model (FEM) [28].

The structural design took place in accordance with the Italian legislation in force [29] integrated with the provisions of EC5 [30] and EC8 [31, 32]. A residential use was chosen, assuming a nominal life Vn equal to 10 years and a class I use (temporary construction).

Such a construction system had the typical box-like behaviour, which was effective in contrast to the horizontal actions generated by earthquakes. The walls were the elements that should resist the horizontal loads due to wind and earthquakes. It should be remembered that wooden structures, by their nature, are less affected by seismic actions, as the seismic action that affects the building is proportional to the masses involved and given that the mass of a wooden structure is considerably lower than the mass of traditional building. It follows that the horizontal actions in the foundation due to the earthquake are lower [33].

Since the module had a low seismic mass, the horizontal wind forces on the structure were higher than the horizontal seismic forces. Therefore, the wind pressure was the only horizontal load that was considered in the structural analysis. The developed hypothesis included the schematization of the structure by means of parallel portals connected with horizontal elements.

The structural analysis was conducted using uniformly distributed vertical loads: one on the roof, to simulate a snow load (60 daN•m$^2$) in accordance with Italian Standard (NTC 2018) EN 1991-1-3, and one (200 daN•m$^2$ - category A) on the floor, in accordance with EN 1991-1-1 [34, 35]. A finite element method (FEM) with a non-linear dynamic analysis was used to verify the structure strength according to Eurocode 5 [36] (Figure 4). The stiffness of the wall panel connection with the wood portals was simulated by a semi-rigid reaction of the moment resisting connection. In particular, the FE model highlighted ductile behaviour with a higher incremental deformation at low loads, whereas it showed lower incremental deformation at high loads. This capacity allowed the structure to better withstand cyclic forces, such as seismic or wind gusts, because part of the energy is dissipated in the deformation work [37]. The FEM analysis highlighted the structure's capacity to withstand wind with a velocity of 72 m•s$^{-1}$ corresponding to the F3 of the enhanced Fujita Scale (EF Scale) of tornado damage intensity [38].

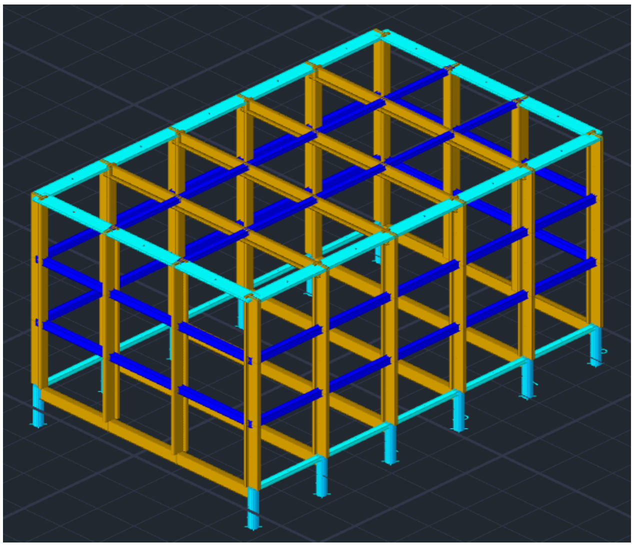


**Figure 4. 3D structural model of the house module M5**

The F3 level on the EF scale represents the damage caused by a strong tornado, *i.e.*, roofs and numerous outside walls blown away from frame homes; all trees in its path uprooted and/or lofted; second floor of two-story homes destroyed; many windows of high rises blown out; radio towers blown down; metal buildings (*i.e.*, factories, power plants, and construction sites) are heavily damaged, sometimes completely destroyed; and large vehicles, such as tractors, buses, and forklifts, blown from their original positions (which only has a 4.9% mean probability of happening).

## 2.2. Thermal Analysis

A thermal performance analysis of the LTH was carried out by means of EnergyPlus software. This software is used to obtain the building energy consumption for heating, cooling, ventilation, lighting and plug and process loads. It allows setting different parameters for the modelling of structures and systems. In particular, it was chosen because it can recreate very precisely the thermal behaviour of active materials like PCM. The simulation was conducted with reference to the weather data of Reggio Calabria (south Italy, 38.1° N, 15.6° E, CSa (Figure 5) following the Koppen classification) with typical Mediterranean climate features [39]. In the past, various housing solutions made of natural materials were proposed [40-42]. The peculiarity of the dwelling unit in question was the stratigraphy of the base module that, in addition to natural materials, such as cork, which has excellent thermal properties, also presented a layer of PCM (Phase Change Material), which is an "active" element. The thermal and optical properties of the analysed LTH materials are shown in Table 1. The PCM material layer in the walls played an important role in the global thermal performance of the LTH. These materials made it possible to improve the thermal behaviour of the building envelope, especially in summer operating conditions. In fact, in summer, the heat flow transferred from the external to the internal environment is attenuated and delayed because it is stored in the PCM during liquefaction in the morning; this latent heat is discharged at night as the PCM solidifies. This is more likely to contain the daily temperature excursion, keep the internal excursion conditions close to those of summer comfort and reduce consumption related to air conditioning. Advantages can also be obtained in winter operation under certain operating conditions. The choice of thickness, position and type of the PCM layer were established on the basis of the analysis carried out by Bruno et al. [43]. In particular, a bio-PCM product encapsulated in proper sheets with a melting temperature of 23 °C was selected for the configuration in exam.

**Figure 5. Map of the study area**

**Table 1. Thermophysical and optical properties of the materials involved in the wall, roof and floor structures for the LTH**

| **Material** | **Thermal conductivity [W/(m·K)]** | **Heat specific capacity [J/(kg·K)]** | **Density [kg/m$^3$]** | **Thermal Resistance [W/(m$^2$·K)]** | **Emissivity [-]** | **Solar / Visible absorbance [-]** | **Thickness [cm]** |
|---|---|---|---|---|---|---|---|
| Cork (external) | 0.052 | 2491.9 | 145.85 | / | 0.94 | 0.3 | 6 |
| Air | / | 1004.5 | 1.225 | 0.180 | 0.9 | 0.7 | 3 |
| OSB | 0.15 | 2700 | 550 | / | 0.6 | 0.6 | 2 |
| bio-PCM 23C | 0.815 | 3140 | 929 | / | 0.9 | 0.7 | 2.4 |
| Air | / | 1004.5 | 1.225 | 0.180 | 0.9 | 0.7 | 0.6 |
| Cork (internal) | 0.052 | 2491.9 | 145.85 | / | 0.94 | 0.3 | 6 |
| **FLOOR STRUCTURES** | | | | | | | |
| **Material** | **Thermal conductivity [W/(m·K)]** | **Heat specific capacity [J/(kg·K)]** | **Density [kg/m$^3$]** | **Thermal Resistance [W/(m$^2$·K)]** | **Emissivity [-]** | **Solar / Visible absorbance [-]** | **Thickness [cm]** |
| Flooring wood blocks | 0.14 | 1200 | 650 | / | 0.9 | 0.78 | 3 |
| Cork | 0.052 | 2491.9 | 145.85 | / | 0.94 | 0.3 | 12 |
| OSB | 0.15 | 2700 | 550 | / | 0.6 | 0.6 | 3 |

The energy analysis was developed with reference to the conditions listed below:

- An electrically powered direct expansion system (split system), with a nominal power of 1.5 kWth for indoor air-conditioning purposes, active 24 h per day;
- An indoor set-point temperature of 20-26°C;
- The presence of 3 windows which ensured internal daylight;
- An entrance door made of two layers of wood panels each 1 cm thick, wrapping a non-ventilated air gap of 3 cm.

Every window had a size of 90×90 cm and was equipped with a 4-12-4 double-pane glazing filled with air and installed on a wooden frame. An internal shading device with a high reflection coefficient was included for the control of solar gains.

The thermal transmittances and the normal solar factor of the windows were calculated for the various envelope structures (Table 2) [44].

**Table 2. Transmittances and threshold values for the various structures of the LTH envelope**

| Structure | U [W/(m²·K)] | SF |
|---|---|---|
| Vertical walls | 0.336 (0.430) | - |
| Ceiling | 0.336 (0.350) | |
| Floor module | 0.341 (0.440) | - |
| Window module | 1.966 (3.000) | 0.687 (0.350) |
| Door | 2.084 (3.000) | - |

Thermal energy demands, internal energy gains and a natural ventilation rate were set following national regulations (Italian standard UNI/TS 11300-1:2014 [45]) that describe standardized procedures for building energy analyses.

The energy analysis of the LTH was carried out by means of the software EnergyPlus and the model developed was graphed in Figure 6.

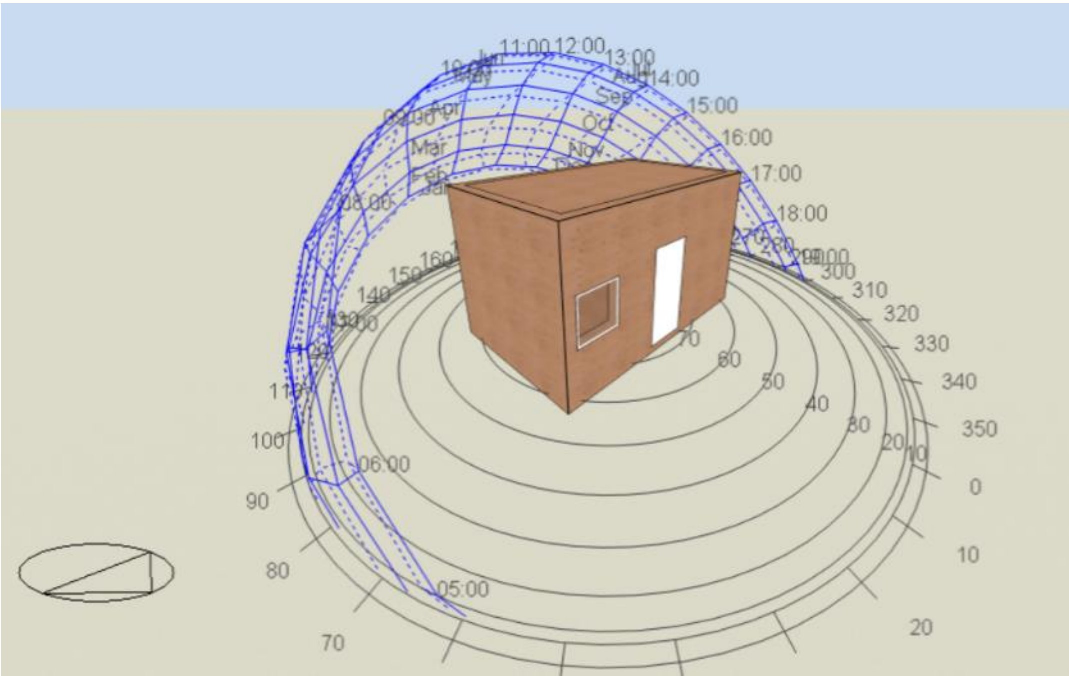



**Figure 6. View of the reference model implemented in EnergyPlus**

The monthly energy used to maintain a set-point indoor temperature of the LTH of 20-26°C (Figure 7) was obtained through the energy analysis and the values are shown in Figure 8.

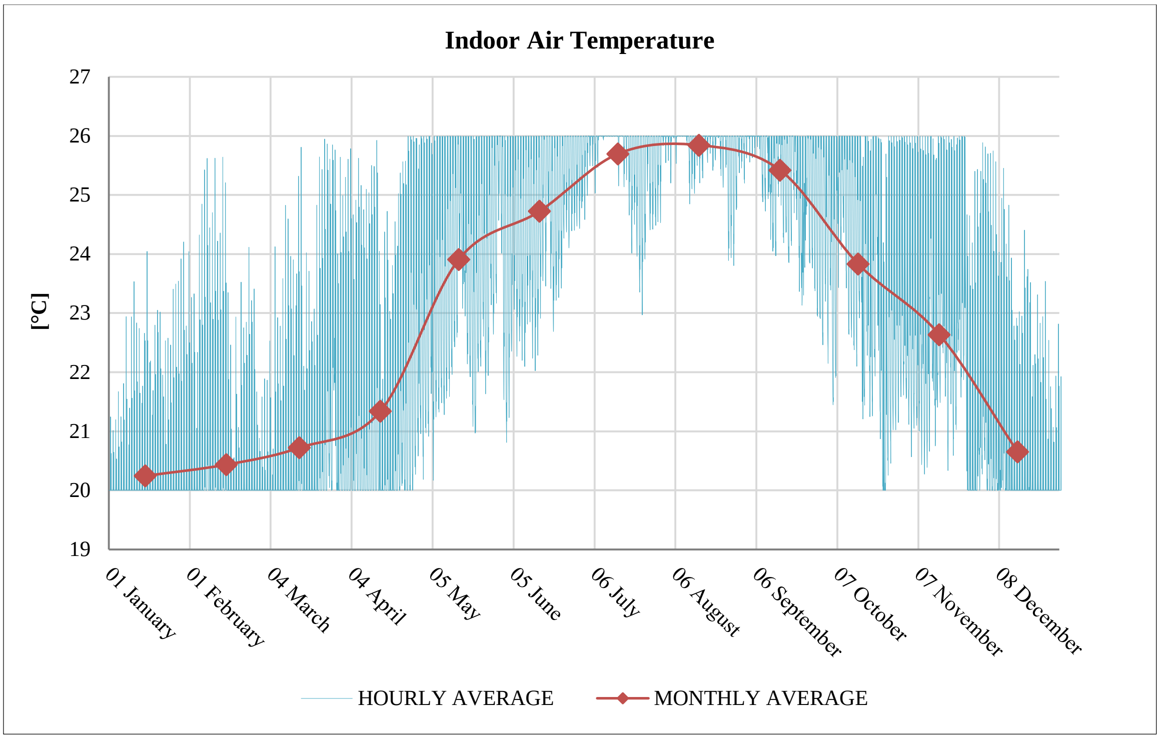
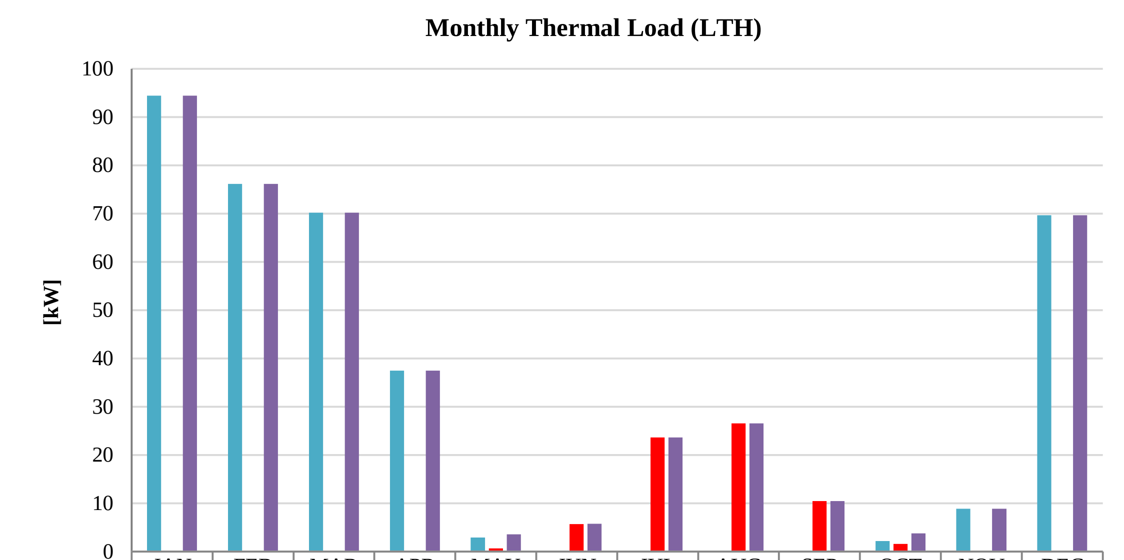



**Figure 7. Hourly and monthly average indoor temperature of the LTH**

Figure 7 shows the hourly average indoor temperature and the monthly average indoor temperature. It is possible to observe that the value of the indoor temperature remains between 20 °C and 26 °C at every moment. The monthly average value of the indoor temperature remains between 20.24 °C and 25.84 °C. The annual average value is about 22.97 °C in this configuration.




| | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| HEATING | 94.44 | 76.18 | 70.18 | 37.50 | 2.90 | 0.06 | 0.00 | 0.00 | 0.00 | 2.15 | 8.88 | 69.68 |
| COOLING | 0.00 | 0.00 | 0.00 | 0.00 | 0.65 | 5.68 | 23.65 | 26.52 | 10.42 | 1.60 | 0.01 | 0.00 |
| TOTAL | 94.44 | 76.18 | 70.18 | 37.50 | 3.55 | 5.74 | 23.65 | 26.52 | 10.42 | 3.75 | 8.88 | 69.68 |

**Figure 8. Monthly thermal load for heating and cooling of the LTH**

The calculated total yearly energy consumption for the LTH proposed was 430.49 kWh.

An energy performance comparison between the LTH and a common Container House (CH) was performed. The energy analysis of the CH was carried out by means of the software EnergyPlus and the model developed was graphed in Figure 9.

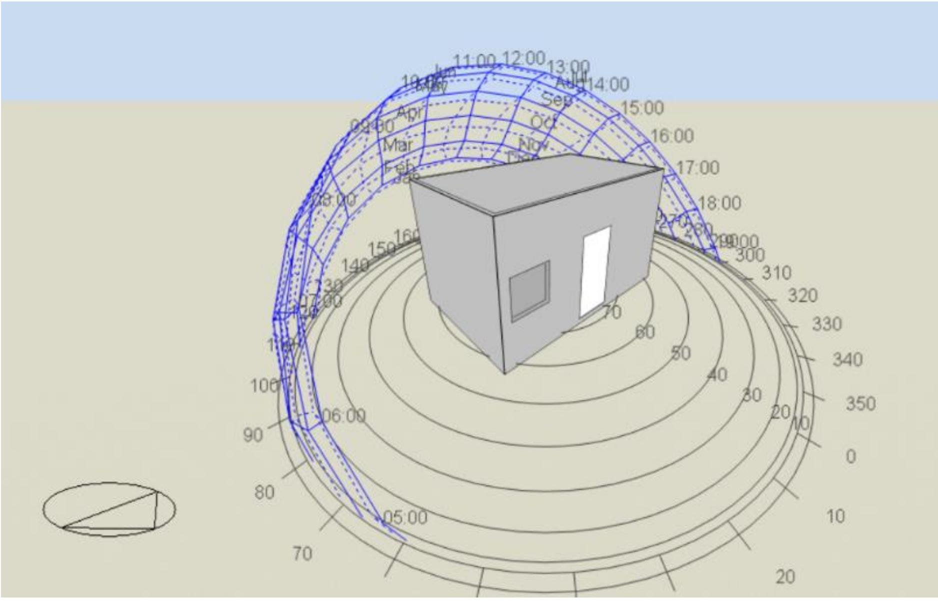


**Figure 9. View of the Container House reference model implemented in EnergyPlus**

The CH compared was chosen with the same dimension and transmittance values as the LTH but with an envelope made of polyurethane sandwich panels (Table 3).

**Table 3. Transmittances and threshold values for the various envelope structures for CH**

| Structure | U [W/(m$^2$·K)] | SF |
|---|---|---|
| Insulated Box module | 0.33 (0.350) | - |
| Floor module | 0.329 (0.440) | - |
| Roof module | 0.33 (0.35) | - |
| Window module | 1.966 (3.000) | 0.687 (0.350) |
| Door | 2.138 (3.000) | - |

The energy analysis was developed with reference to the conditions previously defined for the LTH. The monthly energy used to maintain a set-point temperature of 20-26 °C inside the CH is shown in Figure 10.

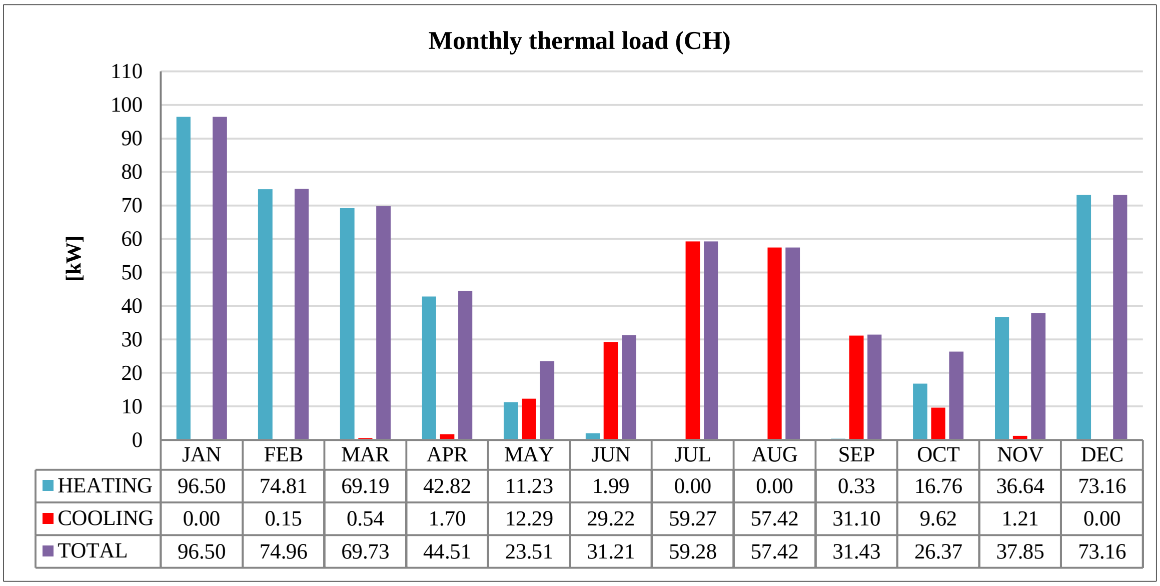



**Figure 10. Monthly thermal load for heating and cooling of the CH**

Figure 11 shows the hourly average indoor temperature and the monthly average indoor temperature. It is possible to observe that the value of the indoor temperature remains between 20 °C and 26 °C at every moment. The monthly average value of the indoor temperature remains between 20.17 °C and 25.53 °C. The annual average value is about 22.42 °C in this configuration.

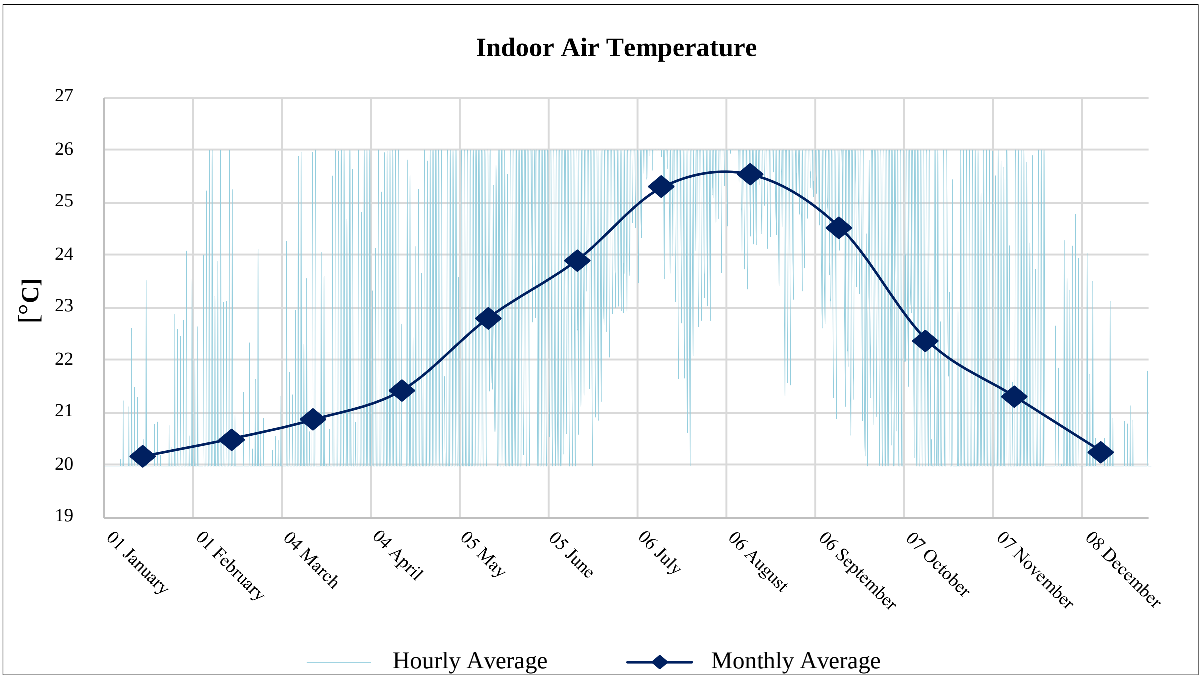



**Figure 11. Hourly and monthly average indoor temperature of the CH**

The calculated total yearly energy consumption for the CH was 625.93 kWh.

From the comparison of the trends of the electricity consumption, it was possible to observe that the two housing units had similar values during the winter months, while, during the summer months, the LTH solution showed significantly lower consumptions. This proved the good energy performance of the proposed solution. The difference in the energy consumption was due to the presence of the layer of PCM inside the module of the LTH housing unit and to the different optical property of the structure's surface under exam. Both characteristics can influence a lot the thermal behaviour of the building as demonstrated by previous research [43, 46].

### 2.3. Sustainability Analysis

To evaluate and control the carbon footprint of these temporary houses it was necessary to apply a specific evaluation model based on the LCA of the construction materials [47]. The life cycle of a temporary house can be divided into three vital stages: mounting, occupancy phase, and dismantling. Many studies found that, for standard buildings, the operational phase accounts for most of the environmental impact during the life cycle, whereas, for temporary houses, the environmental footprint of the materials used is of the greatest importance.

The life cycle of a temporary house usually spans a period of time ranging from a few weeks to a few years [8]. The time depends on the use, on the occupants' needs, and on any unforeseen circumstances. Various factors should be considered when properly analyzing a temporary house, such as easy and fast construction, short delivery time, acceptable privacy, safety conditions, comfort for the occupants, reusability, low cost, minimum impact on the environment and the occupants' culture and participation. The environmental impact assessment of a temporary house is complex, since different stakeholders in the building sector have differing interest and requirements. The first commercially available environmental assessment tool for building was the Building Research Establishment Environmental Assessment Method (BREEAM) developed in 1990 in the UK [48]. Since then, many different tools have been established across the world. These tools cover different stages of a traditional building's life cycle and take different environmental issues into account. The tools can be global, national and, sometimes local. It is very important to adopt a sustainable assessment tool that considers the local conditions, such as the sensitivity of the environment and landscape, availability of energy and materials. The choice of the sustainable building assessment tool has to be based on the use of the building (residential or office building) analyzed. The tools could be applied for different purposes, for example, research, consulting, decision-making and maintenance. Moreover, these tools will be applied by various users, such as researchers, owners, designers, consultants and public administrators. The field of building environmental assessment tools is vast, and the comparison of the tools and their results is difficult, if not impossible [48-50].

The tools are designed for assessing different types of buildings, they emphasize different phases of the life cycle, and rely on different databases, guidelines and questionnaires. Generally, they are based on two different environmental assessment methods: life cycle assessment (LCA) and building environmental assessments (BEA) [51]. The life cycle assessment (LCA) is a commonly used approach to evaluate the environmental building impact during its life cycle [52]. It allows the analysis of the building from the raw material supply stage of its construction, to the operational stage, including how the building will use energy to heat and cool, and the demolition stage and waste processing stage at the end of its life. Generally, common buildings have a long-life cycle and, consequently, the environmental impact of the use phase is greater than the impact of the production phase. Whereas in the case of temporary buildings with a shorter utilization time, the ratio may be the contrary, but could be similar when the usage time increases and the thermal building performance becomes essential to save the energy used. Furthermore, it is unsustainable to design disposable temporary buildings with a short service life [15].

This study aims to assess the potential environmental impact of the analyzed temporary house and considers the recycling of the main materials of which the building is made up.

The LCA methodology framework was used and, in accordance with EN-15978 [53], seven impact categories were evaluated: global warming, acidification, eutrophication, ozone depletion potential, formation of ozone of lower atmosphere, total use of primary energy, biogenic carbon storage. Furthermore, this study takes into account human behaviour, including the instantaneous presence of occupants, the variability of ventilation airflow, and the opening of windows. The analysis was conducted by means of the One click LCA software, which was used to simulate the environmental impact of the different building materials throughout their life cycle. One Click LCA was developed by One Click LCA Ltd and is compatible with EN 15978 standard [53]. It is a web platform for performing Life Cycle Assessment as well as Life Cycle Cost Analysis based on the Environmental Product Declarations (EPDs) in accordance with the ISO 14044 [54] and EN 15804 standards [55]. The software analyses different material impact data from the production and construction of the materials and their use thereof, until the end of life "grave" stage. The LCA analysis model was defined by selecting building materials based on EPDs and considering the type of transportation, as well as the distances from the manufacturers to the building site. Two different scenarios were considered to evaluate the service life period of the building components. According to the Eurocode, the Required Service Life (ReqSL) structural lifetime for was considered to be 10 years, nevertheless, an LCA was carried out to analyze the temporary buildings for a short period of time considering a service life of five years.

The One Click LCA considers the service life of building products in either of the two following ways:

- The amount of time in which a building maintains its function or technical service life.
- The amount of time recommended for heavy use of a particular type of product in buildings that require consistently high-quality standards.

Generally, temporary houses are dismantled after their emergency use and they are stored for successive utilization, thus extending their service life.

In this study, the technical service life of the building's components was considered in relation to the Required Service Life of the building.

The life-cycle stages for the LCA analysis below were considered in accordance with the EN standard:

A1: Raw material extraction and processing, processing of secondary material input (e.g., recycling processes);

A2: Transport to the manufacturer;

A3: Manufacturing;

All three stages include the provision of all materials, products, and energy, as well as waste processing up to the end-of-waste state, or the disposal of the final residues during the product stage. The assessment takes into account only the building and its parts, such as the external walls, floor, columns and load-bearing vertical structures.

A4: Transport to the building site;

A5: Installation into the building.

These stages include all the impacts and aspects related to any losses during the construction process stage (*i.e.*, waste processing and disposal of the lost products and materials).

Furthermore, the following stages were aimed at analysing the impact in use:

B1: The use or application of the installed products;

B2: Maintenance;

B3: Repair;

B4: Replacement;

B5: Refurbishment;

B6: Operational energy use (*e.g.*, operation of the heating system and other building-related installed services);

B7: Operational water use.

Finally, the following stages considered the end of life of the building:

C1: De-construction, demolition;

C2: Transport to waste processing;

C3: Waste processing for reuse, recovery and/or recycling;

C4: Disposal.

Although only modules A1 to A3 are mandatory in product level assessments under EN 15804+A1 [56], and all the other phases are optional, in this study, all of them were considered. The LCA results for the LTH were compared to the LCA results for the CH. A specific mode of transportation and distance from the building material manufacturer to the building site (city of Reggio Calabria) were considered for each of the building materials in the LCA, in order to calculate the impact of transportation.

The annual consumption of the electric energy (stage B6) used by a HVAC system to cool and heat the indoor environment to maintain a constant comfort temperature range between 20-26°C was considered. The energy analysis was performed in dynamic condition assessing the on-site annual temperature. The annual energy used was estimated by means of the DesignBuilder v6 (biblio) software. The result for the timber-cork temporary house was 431 kWh, whereas for the temporary house container it was 626 kWh. Two occupants and an annual water consumption of 50 $m^3$ were considered for each temporary house analysed.

To carry out a more reliable analysis and to get more adequate results for each material in the assessment, a local compensation factor (formerly called Local Compensation), which adjusts the impacts of the material manufactured in another country with a different energy profile to the chosen location, was selected.

The LCA was carried out considering two different scenarios, one of 10 years and the other of 5years ReqSL. For both of them, the results highlighted the higher sustainability of the proposed LTH than that of the CH (Table 4). In particular, the calculated greenhouse gas emissions of the timber-cork temporary house (3.52 E3 $kgCO_2$ eq) were less than 1/2 the gas emissions of the container temporary house (8.53 E3) for a Req SL of 10 years, and about 1/3 for a Req SL of 5 Years (Figure 12).

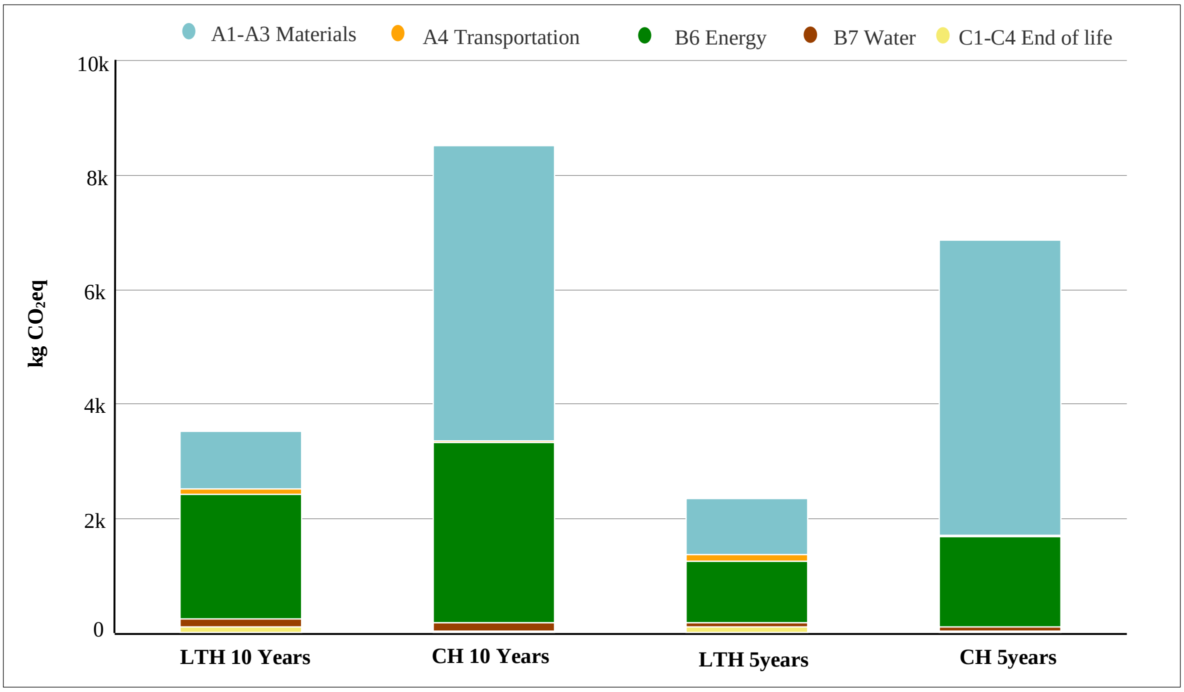



**Figure 12. Global warming for each Life-cycle stage**

## 3. Results

The most interesting result was the value of the Biogenic carbon storage. LTH showed a value of Biogenic carbon storage (7.76E2 $kgCO_2$) about 6 times higher than the temporary house container (1.31E2 $kgCO_2$).

Biogenic carbon within a building product can be considered as a "negative emission". This value was due to the timber and cork components of the temporary house. In fact, when a bio-based material is used as a building product, the carbon is stored as long as the material is used until the end of the life of the building. Presently, the most likely end of life scenario for wood products waste is incineration, in which case the stored carbon is released back to the atmosphere. This means that carbon is stored for a few decades and the total carbon balance over the lifetime of the building is zero. The annual energy consumption plays an important role in the sustainability of the temporary house. The $CO_2$ emissions of the electric energy consumption in use for the LTH with a Req SL of 10 years ( 2175.80 kg $CO_2$) were 62% of the total gas emissions for all the life cycle stages, while those of the electric energy consumption in use for the temporary house container (3164.20 kg $CO_2$ ) with the same ReqSL were only 70%. The high sustainability of the LTH is definitively due to:

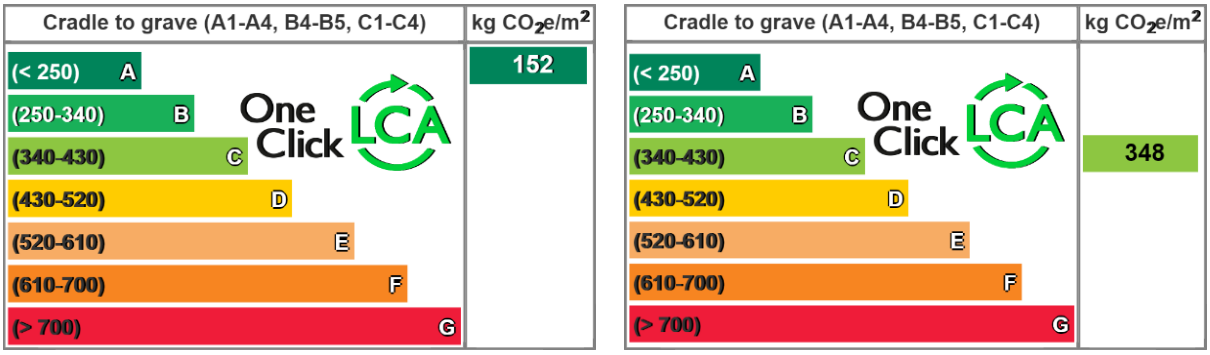
- The low environmental impact of the component materials used for the building;
- The biogenic carbon storage of timber and cork;
- The low energy consumption in use.

Moreover, the distance of transportation from the manufacturer to the construction site of the building material is very important for the environmental impact of the construction. The cork and the pine timber are materials widely found in the area of the Mediterranean forests. Therefore, the distance of transportation is shorter than that of the sandwich panel with polyurethane, which was used for the house container building and manufactured in Northern Europe. The energy usage is another factor which depends on the site and, in particular, on the climate of the site. The energy usage for the temporary houses which were analysed was calculated to maintain a comfortable temperature inside the house over the year, which is clearly dependent on the outside climate. For these reasons, the impact value, which should be calculated with specific reference to the site, could be variable.

A benchmark analysis was carried out in accordance with the Carbon Heroes Benchmark Program (CHBP). The CHBP is a cooperative initiative for carbon profiling for building types across different countries, which was developed through a standardized life cycle model. The data used in the CHBP were anonymized, and implemented the EN 15978/ISO 21930 [53] standards as the basis of their measurement, and included life-cycle stages A1-A3, A4, B4-B5, and C1-C4. The results of the benchmarking were shown in graphical forms as a performance metric that was easy to read (Figure 13). The range is divided into 7 (seven) equally distributed bands. The lower and upper extremes of the range fall within bands “A” and “G”, respectively. A benchmark analysis of the two compared temporary houses was carried out by means the One click LCA online software. The LTH with a value of 152 kg $CO_2/m^2$ emissions falls within band A, whereas the CH with a value of 348 kg $CO_2/m^2$ emissions falls within band C, although it is necessary to specify that the sustainability value of the CH could be further increased by using recycled containers [57]. The benchmark analysis showed the high sustainability of the LTH proposed compared to similar buildings in the same region (Reggio Calabria).

**Table 4. Life cycle assessment results**

| Impact category | Unit | RESULTS | | | |
|---|---|---|---|---|---|
| | | LTH 10 years | CH 10 years | LTH 5 years | CH 5 years |
| Global warming potential (greenhouse gases) | $kgCO_2$ eq | 3.52E3 | 8.53E3 | 2.36E3 | 6.87E3 |
| Acidification potential | $kgSO_2$ eq | 4.91E2 | 2.6E1 | 4.87E2 | 1.97E1 |
| Eutrophication potential | $kgPO_4$ eq | 6.6E1 | 4.51E0 | 6.5E1 | 3.12E0 |
| Ozone depletion potential | $kgCFC_{11}$eq | 2.5E- 4 | 3.69E- 4 | 1.56E- 4 | 2.38E- 4 |
| Formation of ozone of lower atmosphere | $kgC_2H_4$eq | 3.87E1 | 2.21E0 | 3.85E1 | 1.95E0 |
| Primary energy | MJ | 7.04E4 | 1.28E5 | 4.99E4 | 9.88E4 |
| Biogenic carbon storage | $kgCO_2$eq bio | 7.76E2 | 1.31E2 | 7.76E2 | 1.31E2 |




(a) (b)

**Figure 13. Performance metric Carbon Heroes Benchmark: a) LTH b) CH**

## 4. Discussion

The results highlighted that the sustainability of the temporary house depended strictly on the required service life, the building materials, and the installation site. These three factors were strongly correlated. Each uses building materials and has its own environmental footprint. The required service life was responsible for the total energy consumption. The location of the site and the local environmental conditions had an impact on the level of pollution caused by transportation and played an important role in the energy spent controlling the indoor temperature. At the same time, the building material's thermal performance determined its energy consumption. The biobased materials used (wood and cork) for the proposed LTH limited the use of environmental resources, and the phase change material (PCM) layers, which were integrated in the assembly of side walls and roofs, improved the low heat storage capacity of the envelope. This enabled a significant increase in the heat-storage capacity while maintaining the original wall thicknesses. PCM served as a thermal buffer, which could be useful in regions with wide fluctuations in their daytime temperature because it can help save energy in the indoor environmental control.

Temporary housing is an important architectural theme that will extend to different fields in the future, not only for emergency aims. The demand for new accommodations, above all those of the temporary type, is growing. Society is tackling new challenges, such as people immigrating from war-torn or poverty-stricken countries, urban homeless people, the isolation of infectious patients in a pandemic period, and also the need for small private spaces for city inhabitants. These new needs will be translated into the building of new comfortable temporary houses with high sustainability to reduce the environmental impact of people's accommodation. It is an important goal of the new European Green Deal (https://www.consilium.europa.eu/en/policies/green-deal/), a package of policy initiatives, which aim to set the EU on the path to a green transition, with the ultimate goal of reaching climate neutrality by 2050. As 75% of the EU's greenhouse gas emissions come from energy use and production, the decarbonization of the energy sector is a crucial step towards a climate-neutral EU. The building sector is one of the largest energy consumers in Europe and is responsible for more than one-third of the EU's greenhouse gas emissions. It is very important to apply the principles of sustainability to temporary housing, but it is also very difficult to reach the sustainability goal for this type of building. This is because the environmental impact depends on different local factors, such as the transport distance of the building materials, the predominant site's weather conditions, the availability and type of energy at the site, and, most importantly, the length of time used. These factors make it difficult to generalize the results of the environmental impact and force the designer to analyze the sustainability of each building. The availability of LCA tools analysis, like "One Click LCA" makes this assessment easier and faster since this new tool allows for the sharing of data and models. Only specific data on a specific site can be edited.

## 5. Conclusion

This study proposes a new LTH is proposed and highlights its high sustainability value with specific reference to weather data from a region of southern Italy with typical Mediterranean climate features. The high performance is due essentially to the natural building materials used and also to the high thermal performance caused by the PCM. The results highlighted the importance of the characteristics of the installation site and the accuracy of the analysis and design tools. The integration of design tools was very important, (e.g., DesignBuilder has a native integration with One Click LCA). As for the future of this research activity, a specific Generative Design System will be developed to support the designer in achieving a very accurate and fast design to respond in a short time to housing emergencies in any place and in any situation. The generative design process involves rule definition and result analysis, which are integrated into the design process. This approach is able to provide an optimized solution for structural stability, functionality, aesthetics, and environmental impact. The use of digital-computational resources can take into account the building performance and environmental variables in a design process, accelerating this process without excluding the designer's supervision. The generative design is based on information, such as the number of functions, the number of users, connection types, and connection rules, to generate housing structures with usable functional spaces. The high modularity of the proposed LTH allows for easy application of these computational procedures. The use of these kinds of techniques represents a new way of thinking about architecture without forgetting the main purpose of the design of temporary housing. It also helps to generate more sustainable architectural outcomes. The future of this research activity will be specifically concerned with the development of innovative design tools to support strategies to develop nearly zero-energy (NZE) LTH. This concept design refers to a LTH that has very high energy performance with the use of zero, or very little energy to respond to a growing demand for highly sustainable LTHs.

## 6. Declarations

### 6.1. Author Contributions

Conceptualization, F.B. and S.D.; methodology, F.B. and N.A.; software, F.B. and G.C.; validation, F.B., G.C. and A.R.; formal analysis, V.T; investigation, A.R.; resources, N.A.; data curation, F.B. and N.A.; writing—original draft preparation, F.B.; writing—review and editing, F.B.; visualization, N.A.; supervision, S.D.; project administration, F.B.; funding acquisition, F.B and N.A. All authors have read and agreed to the published version of the manuscript.

### 6.2. Data Availability Statement

The data presented in this study are available in article.


### 6.3. Funding

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### 6.4. Conflicts of Interest

The authors declare no conflict of interest.

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