Green and Transportable Modular Building: a prefabricated prototype of resilient and efficient house

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Abstract. Remote working proved to be an advantage in terms energy-saving as well as, for many, in terms of quality of life, while it was a necessity during the pandemic crisis of 2020/2021. This new habit is now promoted by many big enterprises due to associated cost savings. Some experiences of remote working in different locations have started to be supported by incentives in small municipalities to repopulate remote locations in Italy and people are now more inclined to move not just for vacation. These conditions could lead to a sort of “climatic nomadism” achievable, among other, through transportable homes. The net-zero energy Green and Transportable Modular Building (GTMB) project is able to cut its environmental impact. It can assume different configurations according to the user’s needs. The house is based on a timber construction system, easily adjustable and adaptable according to a modular framework. The energy performance has been simulated by means of BIM/BEM methodologies. The building has been tested in two different climates and configurations according to variable social interaction. The energy balance of the house in the life cycle showed the achievement of a carbon zero balance mainly due to timber technology, a heat pump, and PV integration.

1. Introduction

The recent pandemic crisis and associated remote working have created a new context in the effort to mitigate global warming and climate change. Scientific research has long shown the significant contribution of the building sector to greenhouse gas emissions [1].

The European Green Deal [2] promotes sustainability [4] in transportation, construction and production for the future communities and it has supported renovation strategies for the existing buildings and energy efficiency improvement in the new construction [4]. These goals can be strongly supported by digital technologies and digitization of processes [5][6]. Remote working from home can reduce pollution due to transportation, increase energy savings in office buildings and create new living styles that are no longer tied to a specific location. This can encourage a “nomadic” lifestyle that can be enabled by transportable houses. The Green and Transportable Modular Building (GTMB) project presented in this paper proposes a carbon zero building, which uses photovoltaic energy and minimizes the environmental load [7], while creating a sustainable [8], high-quality, comfortable living space adaptable in multiple environmental conditions and supporting new nomadic lifestyles [9]. The project
is based on a timber modular flexible system that can be organized with different configurations, easily adjustable and adaptable [10], allowing also building transportation.

2. Methodology
A BIM (Building Information Modeling) to BEM (Building Energy Modeling) methodology has been developed to design the prototype and extract information to calculate the energy impact in the lifecycle. In Figure 1 the research workflow is presented and the calculation methodologies included. In order to ensure the zero carbon goal, the embodied energy and the environmental impact, the energy consumption in the running phase and the transportation emissions have been calculated.

![Figure 1: Research and calculation workflow](image)

The zero-carbon modular house has been analyzed in two different climates checking the adaptability of the envelope’s energy performance and technology. A BIM model has been used to define the geometry, the envelope solutions, and the quantity takeoff to calculate the embodied energy in the construction materials and the CO2 emissions due to transportation that are related to the weight of the modular timber structure to be moved from the first location to the second, assumed for a typical year of the nomad user. A timber prefabricated structure has been used with eco-sustainable insulation materials, checking the EPD (Environmental Product Declaration) database, in order to shrink the environmental impact. Two different configurations of the GTMB house have been designed according to the two locations (i.e. Italy and Norway). The first solution is called ITB (Italy Based) and the second one is called LET (Low Emission Transport). The energy performance has been preliminarily calculated in the design phase to check the impact of different design choices while a dynamic detailed calculation was performed a) with a standard housing schedule of use and b) with a customized schedule for taking account of the occupancy variable. Renewable energy systems have been sized to make the GTMB energetically self-sufficient.

3. Case of study
A user centered design approach has been adopted for defining the space requirements, the schedule of use and the transportation path. The space and energy requirements (zero carbon goal) have been translated in the building design and in the envelope and systems technological solutions. The house has been placed in Brescia, Italy and Oslo, Norway. The energy needs have been assessed for a standard year in Italy and a standard year in Norway and then for a composite nomad year (50% of the time in each location). The transportation of the ITB solution has been evaluated for the transportation finding a high impact that has been reduced by reconfiguring and compacting the house in the LET solution to achieve a sustainable result. The user will be in Italy in a wider configuration of the house and then the modular house is compacted to be transported to a second location (Section 3.3).

3.1. Climate and location
Two different climates, Brescia (Italy) and Oslo (Norway), have been compared in order to adapt the building and therefore outline different periods of stay. The assumption of the described nomad lifestyle
is that the user will be in Brescia (annual average outdoor air temperature = 12°C, high relative humidity with 57% of recorded values > 80%) during the winter season (from October to March). In the summer season the user will move to Oslo (annual average outdoor air temperature = 7°C, mild relative humidity with 49% of the recorded values between 60 and 80% and the 33% of the recorded values > 80%).

3.2. Building envelope
Based on the locations and regulations, the limits of thermal transmittance were defined. The climate zones have been classified according to degree-days. The degree days are 2410 in Brescia and 3725 in Oslo.

3.3. Building modelling
The GTMB is composed by four types (S01 to S04) of prefabricated timber modules with different sizes. The modules are 3.9 m width and 3.25 m height with variable length (S01=4.17 m; S02 = 5.54 m; S03 = 6.64 m; S04 = 7.69 m). In Figure 2, a representation of the organization of the modules for the solutions ITB and LET is shown. The ITB has 5 modules (S01, S02, S03x2, S04) with a total area of 119.7 m² and a volume of 389 m³ while the compact version LET consists of 3 modules (S01, S03x2) with a total area of 68.1 m² and a volume of 221.3 m³. BIM (Figure 3) has been used to define the architectural model and the construction materials. The compactness of the LET solution reduces the environmental impact for transportation in a size that is compatible with the life of the user. The flexibility of the system allows different modules configurations.

3.4. Energy for transportation
A calculation of the CO₂ emissions for the transportation of the modular house from Italy to Norway has been performed based on the data given by a suitable company (4SPRINGS) that transports prefabricated buildings. In order to verify if the modules could be effectively transported by a 40t truck, the total weight of the structural elements was calculated. Furthermore, the weight of the solar panels was added. Then through the web portal PTV Map&Guide the specific CO₂ emissions per km of the truck during the journey were computed.

3.5. Embodied energy
For each structural element the embodied energy has been defined. The combination of different sustainable materials ensured a negative GWP (Global Warming Potential) and a low NRE (Non-Renewable Energy). Through the adoption of the X-lam structure it has been possible to strongly reduce...
the environmental impact. The materials have been selected based on the EPDs and the IBO (Österreichisches Institut für Baubiologie und Bauökologie GmbH) database.

3.6. Energy performance
The heating and cooling energy demand has been calculated in the preliminary design phase with a semi-dynamic software and in the detailed design phase by a fully dynamic simulation based on the hourly climate data. Two different schedules of use have been defined, the first one considering a “standard” user (24h with same set point temperature, internal gains, ventilation rate) and a second one with a customized “occupancy” considering a specific daily routine (i.e. user out of house 10-12 and 16-19) and realistically varying the above mentioned variables.

3.7. Energy consumption
The total energy consumption of the house has been calculated considering the installation of an AHP (air-to-air heat pump) for thermal uses. DHW (domestic hot water) production and electricity for appliances have additionally been considered.

3.8. Renewable energy
In order to define a NZEB a PV (photovoltaic system) is integrated to provide energy to the AHP and a solar thermal system for DHW has been sized. The stand-alone PV system is sized according to the energy needs in the different locations (Table 1), the peak power is 4.14 kWp and the calculated solar cover is 100%.

| Table 1: PV system components |
|-------------------------------|
| **Type**            | **Number** | **Weight (kg)** | **Dimensions (mm)** |
| Photovoltaic module     | Luxor Eco line 60/230 W | 18 | 3.25 | 936x1166 |
| Regulator             | Eltek Flatpack2 481500 MPPT | 3 | 5.9 | 109x41x107 |
| Battery               | Ecosafe TYS-7 Tubular-Plate | 24 | 40.5 | 191x210x684 |
| Inverter              | Victron Multiplus 48/3000/35-16 | 1 | 10 | 375x214x110 |

4. Results

4.1. Energy for transportation
The calculations of CO2 emissions have been differentiated according to the two solutions, showing that the best alternative is to transport the compact LET solution. In fact, LET requires only one truck that produces 886 kg of CO2, while ITB, due to weight and space issues, needs two trucks and impacts with 1721 kg of CO2 (Table 2).

| Table 2: CO2 emissions results |
|-------------------------------|
| **Solution** | **Floor**     | **Kg CO2/km** | **km** | **kg CO2** |
| ITB solution | Ground Floor  | 0.417         | 875.18 + 845.74 = 1720.92 |
|              | First Floor   | 0.403         | 2098.76 |
| LET solution | Ground and First Floor | 0.422 | 885.61 |

4.2. Embodied Energy
In order to quantify the embodied energy, calculations including NRE (Not Renewable Energy), RE (Renewable Energy) and GWP (Global Warming Potential) have been performed and the results are: 1.94 GJ/m² for NRE, which is the 25% less than a BAU (building as usual) solution in the national construction context, 5.07 GJ/m² for RE and -30 tons CO2/m² thanks to the timber technological solutions (Table 3).
Table 3: Embodied Energy results

| Material            | NRE (GJ/m²) | RE (GJ/m²) | GWP (kg CO₂eq/m²) |
|---------------------|-------------|------------|-------------------|
| Ground floor slab   | 0.65        | 1.80       | -10'327           |
| First floor slab    | 0.54        | 1.23       | -537              |
| Walls               | 0.38        | 0.92       | -15'434           |
| Roof                | 0.36        | 1.12       | -4'338            |
| TOTAL               | 1.94        | 5.07       | -30'151           |

4.3. Global Energy Performance
The global performance calculation considers the house located six months in Brescia and six months in Oslo maximizing the energy saving and user comfort. The preliminary calculation estimates a total heating and cooling demand of respectively 18.1 and 7 kWh/m² year. In the detailed calculation the “standard” schedule results in 13.63 kWh/m² of heating and 1.68 kWh/m² for cooling while for the customized schedule “occupancy” the results are 11.77 kWh/m² for heating and 1.57 kWh/m² for cooling with a reduction of 20%. In Figure 4 a monthly comparison is reported. It is noteworthy that the detailed and customized calculation shows a 47% difference with the preliminary analysis showing how a user centred assessment is crucial in a reliable NZEB definition. Figure 5 shows energy consumption as a percentage considering the different segments of consumption and how the weight of electrical appliances in the NZEB represent the main energy cost.

Figure 4: a) Heating and b) Cooling energy comparison: preliminary analysis and detailed calculation with “occupancy” and “standard” schedule

Figure 5: a) Total energy comparison: preliminary analysis and detailed calculation with “occupancy” and “standard” schedule; b) Total energy consumption, HVAC, electrical devices, DHW
5. Discussion and conclusion
The GTMB shows how a comprehensive approach can support the zero-carbon design and how a climate nomadism coupled with remote working can support energy saving. As shown in Table 4, the total consumption, including the energy consumed for electrical devices, domestic hot water (DHW), heating, ventilation, and air conditioning (HVAC) in a full year in Italy is 46.8 kWh/m² and in a full year in Norway is 61.64 kWh/m². A mixed nomadic solution has been tested minimizing the energy consumption and achieving 39.7 kWh/m² with six months in Brescia (where the winter is milder) and six months in Oslo (where the summer is colder).

Table 4: Total energy consumption for different solution

|                     | Brescia (kWh/m²) | Oslo (kWh/m²) | Nomad solution (kWh/m²) |
|---------------------|-----------------|---------------|------------------------|
| Electric devices    | 16.35           | 16.35         | 16.35                  |
| DHW                 | 10.01           | 10.01         | 10.01                  |
| HVAC                | 20.44           | 35.28         | 13.34                  |
| TOTAL               | **46.80**       | **61.64**     | **39.70**              |

The CO₂ emissions avoided with the use of renewables (i.e. a photovoltaic system) are calculated in about 3.7 tonCO₂eq and 1.6 tonCO₂eq, while the GWP of the whole building is ~28.5 tonCO₂/m² due to the use of low carbon structural and envelope technologies. The environmental impact for the transportation in the tested scenario amounts to 0.88 tonCO₂eq, and thus the energy balance of the building is demonstrated to be carbon zero.

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