# Life Cycle Assessment of a Mobile Tiny House Made with Sustainable Materials and Design Implications

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**Abstract.** Nowadays, relevant design challenges include the need to use sustainable materials that allow designing products with a lower environmental impact. The construction sector is currently undergoing a slow but continuous change towards the use of sustainable materials. One of the most generalized methods for assessing sustainability is the Life Cycle Assessment (LCA), which aims to analyze and compare product alternatives to minimize the environmental impact of a product or a process. In this work, the LCA method has been applied to a mobile tiny house prototype built with sustainable materials, such as hemp bricks or wood. The ISO 14040 and the EN 15804 standards were followed. The life stages calculated are hemp cultivation and processing, production of the hemp brick, construction of the tiny house and transportation. The results show that the most significant impact comes from the production of titanium sheet metal, wood, bricks, and the transport of raw materials. The results suggest that hemp bricks are a sustainable alternative, but they need to be combined with the right manufacturing and transportation processes. This research offers insights into how to introduce sustainability in the building sector through early design decisions, such as the selection of materials.

**Keywords:** Life Cycle Assessment · Tiny house · Sustainable design · Biomaterials

## 1 Introduction

Sustainability promotes the optimization of resources for making their best use possible [1], so that human needs are satisfied without compromising the resources provided by ecosystems [2]. To pursue sustainability goals, especially in the fields of product and service design, design engineering is one of the most important drivers [3]. This applies to the construction sector and to the design of architectural spaces too. Design decisions involve how products will be used and how their end of life will be, the actions to be taken as regards the handling of resources. These intertwined requirements can be managed by considering sustainability and user behavior from the beginning of design processes through strategies, as for example the ones proposed by [4] or [5].

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Introducing sustainable features in products and buildings gives rise to new challenges. Designers have to identify the most suitable mix of materials that allows an optimal and sustainable performance, while, at the same time, ensuring competitive prices for the purchaser. Assessment procedures are therefore crucial in this context; several metrics and indicators for sustainability assessment have been developed accordingly [6–10]. One of the most acknowledged methods both in product and construction sectors is the Life Cycle Assessment (LCA). LCA is a quantitative assessment approach whose main objective is to analyze technical systems, such as products and processes, in terms of their environmental impact. As the name suggests, a lifecycle approach is considered in LCA. To assess sustainability in buildings, all the lifecycle stages should be taken in consideration, from the extraction and manufacturing of raw materials to the end of life and dismantling [11]. The main objective of the assessment of buildings' sustainability is to obtain information for decision-making during all the stages of a building [12]. However, many contributions in the building sector consider a restricted number of lifecycle stages and operations, e.g., [13, 14]; this paper is of no exception. One of the reasons is the fact that the expected life of buildings is several decades and that simulations are therefore needed. In addition, the study of a limited set of phases is sometimes sufficient to make decisions on materials to be chosen, despite operational phases are typically attributed of major environmental impacts [15–17]. Otherwise said, reliable analyses can be carried out by using primary data if a prototype is built. The same approach is followed in this work, where LCA is applied to a prototype of a 25-square-meter mobile tiny house; details are provided in Sect. 2. To run the LCA, the stages regarding production and manufacturing of the house and the construction of the prototype are actually analyzed in the paper (see Sect. 3).

Section 4 is earmarked to presenting data inventory. The LCA outcomes are presented in Sect. 5 along with a comparison of the results with other case studies, which was enabled by choosing one square meter of floor as a functional unit of the analysis.

As highlighted in the concluding Sect. 6, the outcomes are considered sufficiently informative to steer early design stages, where the most important features of the product are defined, including materials [18]. This is very useful, as decisions and changes can be easily made with limited costs and consequences in the front end of the design process [19].

## 2 Context of the Work

The case study for the LCA analysis was a prototype of a mobile house that has been designed and constructed to represent a sustainable example of building due to the materials used and their local origin. The construction of the prototype is part of the project Tiny FOP MOB, as detailed in the acknowledgements. The name of the project is used hereinafter to indicate the prototype too. The scope was to create a Real-world Laboratory, which could be moved in different locations in the Vintschgau Valley, Italy, for evaluation scopes. This explains the reasons for the mobility of the tiny house, which was achieved by means of a trailer, which, as a consequence, limited its size. Figure 1 shows the exterior (a) and interior (b) of the tiny house.

The prototype has a total weight of approximately 12 tons. Its structure is made primarily of hemp bricks, used to construct load-bearing walls, and wood for the frame, floor, roof and external coating. The bricks have been assembled using a natural mortar. The interior surface has been finished using plaster made of hemp fiber and natural hydraulic lime. Spruce wood has been used for the frame, beams and screed, while larch has been employed for the floor, the false ceiling and the external cladding. Other materials used are a galvanized titanium sheet for the roof and a vapor barrier made of wood fiber.

a b

**Fig. 1.** External (a) and internal (b) view of the mobile tiny house.

## 3 Methodology, Goal and Scope of the Study

The LCA has been conducted following the ISO 14040 and the EN 15804 standards. Specifically, the EN 15804 was developed for the LCA of building materials and provides a basis for Environmental Product Declarations. The goal of the research is to calculate the life cycle impact of the Tiny FOP MOB. The defined functional unit is a square meter of floor area of the prototype.

EN 15978 describes several stages of a building life cycle. Stage A includes all the activities from raw material extraction to building construction. Stage B addresses the useful life of the building and its maintenance and repair processes. Stage C includes the end of life, dismantling and eventual recycling of materials. Stage D accounts for the potential positive impact of reusing materials and components after the end of life. Based on EN15978, this paper identifies the system boundaries in all the activities leading to the construction of the Tiny FOP MOB from the production of its raw materials.

The life cycle phases analyzed are reported below:

- A1a: Hemp cultivation, harvesting and transportation to the transformation site;
- A1b: Processing of hemp shives for the production of the brick;
- A2: Transport of the hemp shives to the brick production site;
- A3: Production of the hemp brick;
- A4: Transport of all raw materials to the construction site;
- A5: Construction of the tiny house.

The considered stages of the prototype lifecycle are widely presented in the subsections that follow. Figure 2 reports them graphically along with the data used as an input of the LCA analysis.

As mentioned, the decision to focus on the early stages of the prototype's life cycle is primarily due to examining how these initial design choices can affect the environment. Moreover, since the hemp brick used in the construction of the Tiny FOP MOB is a new material on the market, there is no actual end-of-life data, which would prevent the full consideration of the phases indicated in EN 15978.

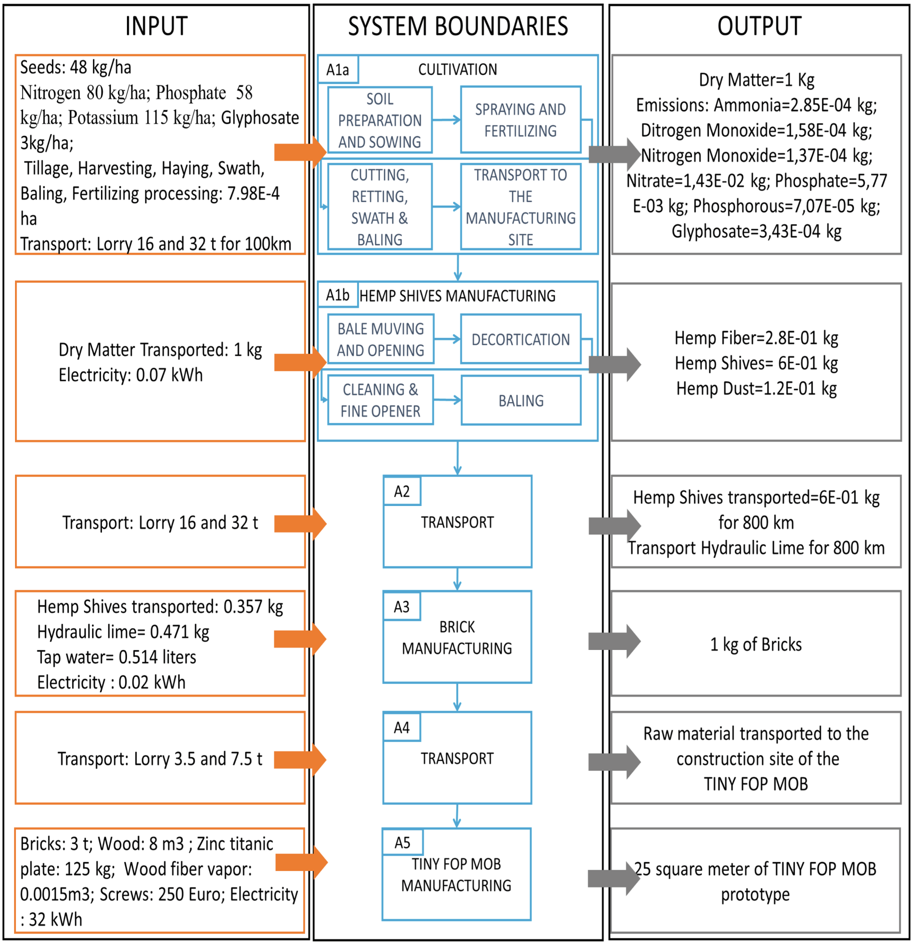


**Fig. 2.** LCA phases and inputs/outputs considered in the process of creation of the tiny house prototype for the environmental assessment of 1 square meter of floor surface

## 4 Data Collection and Life Cycle Inventory

The data has been collected through semi-structured interviews with the main project partners, i.e. the producer of the hemp bricks and the Tiny FOP MOB's constructor.

Further information has been obtained through the analysis of the literature. Data on means of transport, energy consumption and the production of some raw materials (e.g. wood and lime) have been achieved from the Ecoivent version 3.8 database, which includes information on the environmental impacts of various industrial and agricultural processes.

### 4.1 Hemp Cultivation-Stage A1a

For the cultivation of hemp shives, which are the essential element in the mixture for the bricks, a typical Central European cultivation context has been considered. In particular, reference has been made to a study that analyses hemp cultivation in Austria [20], as for the supplier of the Tiny FOP MOB's bricks. The output of the stage provides 1 kg of dry matter. The processes taken into account are soil preparation and sowing, fertilizing, harvesting, baling and transport of the hemp to the transformation site, as reported in Fig. 2.

The sowing rate has been set to 48 kg per hectare, while the fertilizing consisted of 80 kg/ha of nitrate, 58 kg/ha of phosphate and 115 kg/ha of potassium. An herbicide has been also employed in the cultivation, corresponding to approximately 3 kg of glyphosate per hectare. The harvested hemp is finally transported by a lorry, whose weight is between 16 and 32 t, for approximately 100 km to the processing site.

### 4.2 Hemp Shives Production-Stage A1b

Once the hemp is fed into the manufacturing line, the decortication process mechanically removes the fibers from the straw and separate them into fibers, shives, and dust. Considering that the production of hemp per hectare is around 7500 kg, the decortication process resulted in 30% of fiber, 5% waste and the remaining 65% of shives. The environmental assessment of the fiber and the dust are outside of the system boundary. However, those derivatives can be reused for other industrial purposes such as ropes or as a filler in plastics, lime renders or compressed for fuel logs. The production line consumes approximately 0.07 kWh to process 1 kg of hemp and it has been powered by electricity from the grid. The line can process 4 tons of hemp straw per hour.

### 4.3 Hemp Blocks Production-Stage A3

In the production of the hemp bricks, the two materials required are hemp shives and hydraulic lime, which have been delivered in bulk to the production site. Specifically, the hemp shives have been sent from the processing site in Austria to the brick production site in the Vintschgau Valley (Stage A2 in Fig. 2). The distance is approximately 600 km, and a less-than-16-tons truck has been used. The hydraulic lime, instead, has been shipped from Germany in a truck weighing less than 16 tons, for about 800 km.

The raw materials from the storage place have been sent to a mixing machine, where they are finally combined with water. In total, 0.357 kg of hemp shives, 0.471 kg of hydraulic lime and 0.514 L of tap water are necessary to produce 1 kg of hemp bricks. The mixture has been then poured into a cement block mold. The bricks have been finally pressed and air-dried. Once hardened, the blocks have been loaded into pallets and wrapped in nylon film, ready to be transported to the construction site.

The energy consumption of the machinery is allocated by considering the electricity mix for Italy and corresponds to approximately 0.02 kWh to produce 1 kg of brick. In-house movements at the production site have been excluded from the analysis.

### 4.4 Construction of the Tiny Prototype-Stage A5

In the final Tiny FOP MOB's production, all materials have also been assembled at the constructor site in the Vintschgau Valley. In this case, the main operations have been cutting, drilling and screwing. The estimated total energy consumption is 32 kWh.

Raw materials have been sent from local suppliers in the case of hemp bricks (30 km away), wood (14 km away) and titanium sheet (5 km away). The cement and the insulating wall were supplied by companies from Germany, particularly from the Stuttgart area, about 400 km from the construction site. A truck weighing between 3.5 and 7.5 tons has been employed for all transportations (stage A4 in Fig. 2). The handling of raw materials within the construction site has been neglected again.

In total, about 3 tons of hemp bricks have been used to construct the Tiny FOP MOB's perimeter. The total cubic meters of wood are about 8, considering the two different types of timber. The zinc plate weighed 125 kg, and 0.0015 $m^3$ have been allocated to the wood fiber vapor brake. In assembling the wood and other materials, about 250 screws and brackets have been used.

## 5 Results and Discussion

### 5.1 Life Cycle Impact Assessment

The LCA assessment has been carried out by using the acknowledged characterization method CML-IA Baseline, developed by the Institute of Environmental Studies of the University of Leiden [21]. The CML-IA Baseline has been chosen since it is one of the most widely accepted methods in the construction sector [22], which makes it largely adopted also in recent studies [23]. The choice of the method allows us to compare the results obtained in the present study with others available in the literature. CML-IA Baseline allows the determination of the impact that the functional unit has on soil, air and water by analyzing eleven impact categories:

- Abiotic Depletion and Abiotic Depletion fossil that relate to the extraction of minerals and fossil fuels, calculated in Kg Sb equivalent and MJ, respectively;
- Global Warming (GWP 100a) due to the emission of greenhouse gases over a 100-year time interval, calculated in Kg $CO_2$ equivalent;
- Ozone Layer Depletion due to the different gases, measured in Kg CFC-11 equivalent;
- Human toxicity, Freshwater Aquatic Ecotoxicity, Marine aquatic ecotoxicity, and Terrestrial Ecotoxicity, which measure the effects of toxic substances on human health, water, groundwater, marine and terrestrial systems, respectively, indicated in Kg CFC-11 equivalent;

- Photochemical Oxidation, which measures the formation of reactive substances (mainly ozone), which can be harmful to human health and ecosystems, calculated in Kg $C_2H_4$ equivalent;
- Acidification, which measures the production of acidifying substances that damage terrestrial ecosystems, expressed in Kg $SO_2$ equivalent;
- Eutrophication that includes all impacts due to excessive levels of macronutrients in the environment, measured in Kg $PO_4$ equivalent.

The analyses have been carried out with the SimaPro software, version 8.0.2, considering a lifetime of 100 years.

## 5.2 CML-IA Baseline Results for the Mobile Tiny House Prototype

Figure 3 shows the normalized results on the different environmental impact categories according to the CML-IA Baseline method for the functional unit of the whole prototype, i.e. one square meter of floor. For each indicator, normalization factors are based on the average yearly environmental load worldwide, divided by the number of inhabitants for the years 1990 and 1995. The calculation is provided by the SimaPro software.

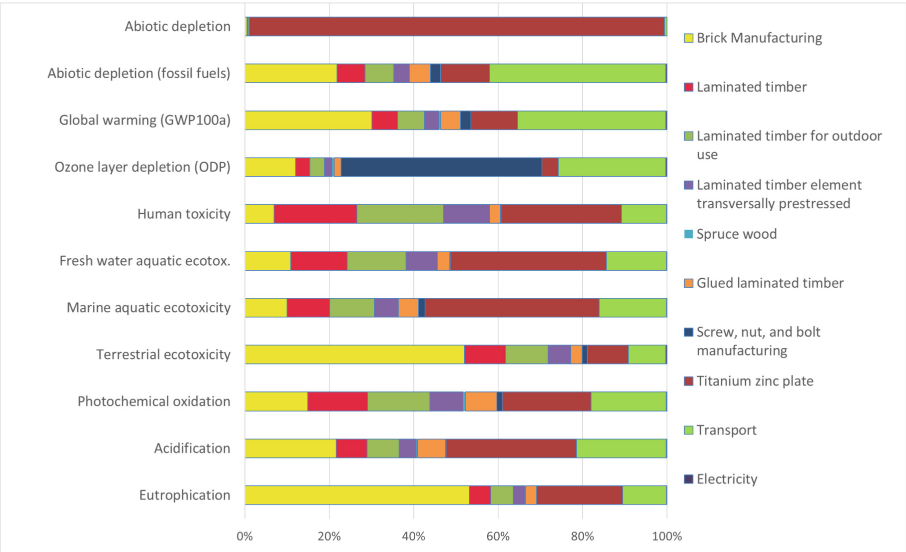


**Fig. 3.** CML-IA results for each impact category.

Based on Fig. 3, the processes with the most significant impact on total emissions are the production of titanium sheet metal, wood, bricks, and the transport of raw materials.

The titanium sheet used for the Tiny FOP MOB roof represents almost the entire category of Abiotic Depletion (98%), being it an alloy that involves extracting minerals from the ground for its production. This material also significantly affects the toxicity caused to water and groundwater (37%) and the marine ecosystem (47%).

Wood has a homogeneous impact on all categories. Considering the wood production as a single item without distinguishing between different typologies, an effect of more than 51% in the Human Toxicity category has emerged. Out of this percentage, 20% is mainly due to the chemicals emitted during the production of laminated wood for outdoor use. An impact of 45% is also observed in the Photochemical Oxidation class, mainly due to a reaction that occurs when the wood is exposed to UV radiation.

Concerning the transport of raw materials to the production site, it can be observed that the most affected categories are the Abiotic Depletion fossil (45%) due to the extraction of fuel and the Global Warming category (35%) due to the emission of greenhouse gases, which also impacts on the Ozone Depletion (25%). These values are mostly related to the presence of raw materials that have been supplied by other countries such as Austria and Germany.

By combining different materials, the hemp bricks do not significantly affect the prototype as a whole, despite their considerable weight in its construction. The highest effect occurs in the Eutrophication (52%) and Terrestrial Ecotoxicity (52%). This is most likely due to the need to use fertilizers and pesticides in hemp cultivation. Another category with a 30% impact is Global Warming due to $CO_2$ emissions in the processing of hemp and in the brick's production.

However, the effect of the biogenic uptake of hemp and the carbonation of lime binder has been neglected in this analysis, as only positive $CO_2$ processes have been calculated. By considering these two aspects, more $CO_2$ is actually retained in the brick production than is emitted. According to examples and studies found in the literature, the amount of $CO_2$ sequestrated is around 18 to 34% of the one emitted during the brick's production and throughout the lifetime of the brick [24]. Hence, considering the $CO_2$ sequestered, it is possible to achieve a negative impact. This demonstrates that the use of hemp is a sustainable choice compared to other materials, nowadays prevalent.

In Table 1, the results achieved in the project prototype are compared with two other studies in terms of: building characteristics; materials used in their production; characterization method for the LCA calculation; total $CO_2$ emissions into the atmosphere (per kg of the same functional unit). Since the $CO_2$ emitted is the most common category assessed in the literature, it has been decided to compare the case study with a wooden [25] and a traditional [26] building in terms of this value. The choice of the two cases was made to try to directly compare with other constructions with sustainable materials or cases of traditional buildings. Unfortunately, to the authors' best knowledge and a literature review, there are no cases of LCA analyses examining systems with characteristics (volume, non-residential use, mobility) closer to the Tiny FOP MOB. From Table 1, it can be seen that the two examples have a very different size. The authors have therefore decided to search for and compare structures according to the functional unit of one square meter of floor space to overcome this problem.

The $CO_2$ value of the current study is significantly higher than in the two comparison cases. The difference is primarily ascribable to the design choices made on the prototype. Indeed, the Tiny FOP MOB was designed and built primarily for scientific, divulgation and educational purposes. Some aspects of transporting raw materials and manufacturing have not been considered for tiny houses of a standard size. For example, the fact that the walls are built primarily with hemp bricks entails a higher weight of the house. However,

**Table 1.** Comparison of case studies with wooden and traditional buildings

| | Tiny FOP MOB | [25] | [26] |
|---|---|---|---|
| Functional unit (FU) | 1 $m^2$ of floor surface | 1 $m^2$ of floor surface | 1 $m^2$ of floor surface |
| Building characteristics | 25 $m^2$ of floor surface; energy consumption being calculated | 5-storey building; net floor area 726 $m^2$; operating energy consumption 63 $kWh/m^2/a$ | 5 floors; net floor area 16746 $m^2$, annual heating requirement 56 $kWh/m^2$ |
| Materials | Spruce, larch, hemp bricks | Larch; wooden window frames; concrete; cement; mortar; rubber products; rock wool | Concrete; cement; mortar; rubber products; rock wool |
| Characterization methods | CML-IA Baseline | CML 2001 | CML v4.1 |
| GWP ($kgCO_2e/FU$) | 300 | 42 | 6 |

this design choice was made in order to have a stable structure that could be transported by trailer across different towns. Hence, more material is required in construction than prefabricated units designed for residential buildings are.

There is also a gap between the wooden and the traditional construction. The reason is mainly related to the characteristics of the two buildings. The net floor area of the traditional one is much larger, which distributes the $CO_2$ emission values better over the functional unit. The difference, however, is again a matter of design choices; the project requirements imposed the fabrication of a house transportable on standard truck trailers. So far, in the construction sector, sustainable materials such as hemp and wood are used in small and medium-sized buildings. The structural obstacles of sustainable materials have be overcome in order to start thinking about large traditional sustainable buildings.

## 6 Conclusions

LCA has become a fundamental tool to evaluate choices in terms of resources for the design and construction of buildings. In this study, the use of sustainable materials, such as hemp and wood, has been evaluated through LCA on a prototype of a tiny house built for the Tiny FOP MOB project. The environmental advantages in using sustainable materials, if compared to traditional ones, have been demonstrated.

The results obtained suggest that, on a large scale, this type of building can be a good sustainable choice in combination with optimal design, manufacturing and transportation processes. The example reported in this paper underlines how having so many constraints on the design and construction of the prototype creates disadvantages in terms of sustainability that cannot be compensated by merely using sustainable materials. In this case, design requirements were so constraining that they compromised the design efforts towards sustainability. This brings us back to the widely discussed conflict in the literature between performance and sustainability.

Looking at the future development of the tiny house, the LCA analysis would guarantee the first step to obtaining the energy certification. Hence, there will be a real possibility of moving into the actual production of the tiny house, rethinking its design towards a more sustainable construction.

A further objective would be to combine the LCA analysis with a life cycle cost analysis. In this case, the balance between costs and sustainability will be evaluated, while also contributing to the improvement and evolution of design for sustainability in the early stages. It has been shown that taking costs into account at an early stage of development may help make informed design choices [27, 28]. In this case, the trade-off between sustainability and costs can be effectively considered.

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