UNIVERSITÀ DEGLI STUDI DI PADOVA
Dip. Territorio e Sistemi Agro-Forestali

Corso di laurea magistrale in Scienze Forestali e Ambientali

Environmental assessment of MHM wooden building system

Relatore
Prof. Raffaele Cavalli

Correlatori
Dott.ssa Michela Zanetti
Dott.ssa Francesca Pierobon

Laureanda:
Silvia Santi
Matricola n. 1065586

ANNO ACCADEMICO 2014-2015

Index

List of tables

List of figures

Abstract

According to the IPCC, to deal with global warming and climate change, technological, economic, social and institutional actions need to be undertaken. The building industry is highly pollutant and accounts for 19% of energy-related GHG emissions. Using wood as building material can help to reduce emissions. In this study a life cycle assessment has been performed to assess the emissions to air produced during the manufacturing of a *Massiv-Holz-Mauer* (MHM) wall system. The results have been compared to the LCA of of a traditional brick wall to determine which of the two building systems has the lowest environmental impacts. The core of MHM wall consists of 9 wooden boards layers connected by aluminium nails and it is thermally insulated by wood soft fibreboards. Plaster coverings on the inside and outside complete the wall. The compared masonry wall is a one-brick layer wall insulated with an XPS foam slab and finished with plaster.

The LCA has been set up as a gate-to-gate analysis, using as functional unit for both wall types 1 m^2 of wall, maintaining its wall function over 50 years, and ensuring a thermal transmittance (U-value) of 0.21 W/m^2K. Raw material extraction and building of the house are not included in the system boundaries. GaBi software and CML 2001 – Apr. 2013 impact assessment method have been used to perform the LCA. The impact categories considered are Global Warming Potential (GWP) and Ozone Depletion Potential (ODP), at global scale; Photochemical Ozone Creation Potential (POCP) and Human Toxicity Potential (HTP) at local scale. The models have been made using both primary data and secondary data.. Primary data have been collected for the MHM wall at FBE Woodliving company and Saviane Industria Legnami sawmill. Secondary data have been provided by Ecoinvent database.

The LCA results have shown that the MHM wall construction produces less emissions than the brick wall building materials production. The GWP for MHM is 32.631kg CO_{2eq} which represents 37% of GWP emissions compared to the brick wall, and ODP for MHM (3.935 mg $R11_{eq}$) is the 57% of brick wall ODP. POCP and HTP for MHM are respectively 57%, and 50% of the emissions related to the brick wall building materials production. For MHM, the major contributions to emissions are related to the sawmill process and to the manufacturing of fibreboards, aluminium nails and plasterboard; on the other hand, the brick industry causes the highest emissions for the brick wall production process. A displacement factor of 0.53 t CO_{2eq} per ton of oven-dried wood for MHM building system used in place of the analyzed brick wall has been determined in the defined system boundaries conditions.

In conclusion, it can be said that the studied MHM wood system represents a more environmental sustainable building option than the brick alternative. These results are consistent with the other studies on this topic.

Riassunto

Secondo l'IPCC per affrontare il riscaldamento globale e il cambiamento climatico è necessario intraprendere azioni di tipo tecnologico, economico, sociale ed istituzionale. L'industria dell'edilizia è altamente inquinante ed è responsabile del 19% delle emissioni di gas serra collegate alla produzione di energia. Usare il legno come materiale da costruzione in sostituzione ad altre alternative può servire a diminuire le emissioni. In questo studio è stata effettuata un'analisi del ciclo di vita (*Life Cycle Assessment*, LCA) per determinare quante emissioni vengono immesse nell'aria durante la produzione di 1 m^2 di muro di legno con la tecnologia *Massiv-Holz-Mauer* (MHM).I risultati dell'analisi sono stati confrontati con quelli della LCA della produzione di 1 m^2 di muro di mattoni (tradizionale), per determinare quale dei due sistemi costruttivi ha un minore impatto ambientale in termini di emissioni prodotte. Il muro MHM è costituito da 9 strati di tavole di legno, ogni strato formato da più tavole affiancate; gli strati sono uniti tra loro da chiodi di alluminio e isolate termicamente da pannelli di fibra di legno. Il muro è rivestito da coperture in cartongesso e intonaco. Il muro in muratura impiegato come paragone è un muro in mattoni monostrato con cappotto in polistirene espanso.

I modelli LCA sono state impostati con un approccio *gate-to-gate*, usando un'unità funzionale di 1 m^2 di muro per entrambi i tipi di muro, volto a mantenere la sua funzione per 50 anni e assicurando un valore di trasmittanza termica di 0.21 W/m^{2}K. I confini del sistema includono i processi di fabbricazione dei materiali, il trasporto e l'assemblaggio del muro. L'estrazione delle materie prime e la costruzione della casa non sono compresi. Per effettuare la LCA sono stati utilizzati il software GaBi e il metodo di valutazione di impatto CML 2001 – Apr. 2013. Le categorie di impatto considerate sono il potenziale di riscaldamento globale (*Global Warming Potential*, GWP) e il potenziale di esaurimento dell'ozono (*Ozone Depletion Potential*, ODP) a scala globale; la formazione di smog fotochimico (*Photochemical Ozone Creation Potential*, POCP) e il potenziale di tossicità umana (*Human Toxicity Potential*, HTP) a scala locale. I modelli sono stati costruiti usando dati primari e secondari. I dati primari per MHM sono stati raccolti con la collaborazione dell'azienda FBE Woodliving e della segheria Saviane Industria Legnami. Per i dati secondari è stato usato il database Ecoinvent.

I risultati delle LCA hanno mostrato che il processo di costruzione del muro in MHM produce meno emissioni della produzione dei materiali per il muro di mattoni. Il GWP associato alla fabbricazione del sistema MHM è 32.631kg CO_{2eq} che rappresenta il 37% delle emissioni del GWP del muro in mattoni; l'ODP per MHM (3.935 mg $R11_{eq}$) è il 57% dell'ODP per il muro di mattoni. Il POCP e l'HTP per il muro MHM sono rispettivamente il 57% e il 50% dei corrispondenti indicatori per il muro in mattoni.

Per il muro in MHM i processi che contribuiscono maggiormente alle emissioni sono relativi alla segheria, alla produzione di pannelli in fibra di legno, ai chiodi di alluminio e al cartongesso. Per il muro di mattoni è l'industria di laterizio che causa le maggiori emissioni. Un *displacement factor* (fattore di dislocamento) pari a 0.53 t CO_{2eq} per ogni tonnellata di legno anidro per il sistema costruttivo MHM usato al posto del muro in mattoni è stato determinato nei limiti dei confini del sistema definiti.

In conclusione si può affermare, in linea con gli altri studi in questo campo, che il sistema costruttivo in legno MHM rappresenta un'opzione di costruzione più sostenibile dal punto di vista ambientale rispetto ad un muro tradizionale in mattoni.

1. Introduction

1.1. Global Warming

The IPCC Fifth Assessment Report (AR5) confirms that human influence on the climate system is clear and growing, with impacts observed across all continents and oceans, and states that, with a 95% of confidence, humans are the main cause of the current global warming (IPCC, 2014a). Anthropogenic greenhouse gas (GHG) emissions since the pre-industrial era have driven large increases in the atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Total anthropogenic GHG emissions have continued to increase over 1970 to 2010 with larger absolute increases between 2000 and 2010, despite a growing number of climate change mitigation policies. Emissions of CO_2 from fossil fuel combustion and industrial processes contributed about 78% of the total GHG emissions increase from 1970 to 2010, with a similar percentage contribution for the increase during the period 2000 to 2010; with economic and population growth being the main drivers of this increment.

However, according to the AR5, we have the means to limit climate change and its risks, with solutions that allow for continued economic and human development.

Climate change has the characteristics of a collective action problem at the global scale. Emissions reductions over the next few decades and near zero emissions of CO_2 and other long-lived greenhouse gases by the end of the century is required to likely limit warming to below 2°C relative to pre-industrial level. To reach this goal, technological, economic, social and institutional actions need to be undertaken.

1.2. Role of the building sector

The social, economic and environmental indicators of sustainable development are drawing attention to the construction industry, which is a globally emerging sector, and a highly active industry in both developed and developing countries (Ortiz *et al.*, 2009). At global level the building construction consumes 24% of the raw materials extracted from the lithosphere (Zabalza Bribián *et al.*, 2011). High levels of pollution and emissions from the building industry are the result of the energy consumed during the extraction, processing and transportation of materials (Morel *et al.*, 2001). According to the IPCC Fifth Assessment Report , in 2010 buildings accounted for 19% of energy-related GHG emissions (including electricity-related)(IPCC, 2014b). The demand for energy in buildings in their life cycle is both direct and indirect. Direct energy is used for construction, operation, renovation, and demolition of a building, while indirect energy is consumed by a building for the production of the materials used in its construction and technical installations (Sartori and Hestnes, 2007).

1.3. Wood as building material

Wood is commonly regarded as the most environmental-friendly material in building design and construction (Li and Xie, 2013). Several studies have demonstrated that the use of wood in building in substitution to other materials helps to reduce the CO_2 emissions (Buchanan and Honey, 1994; Goverse *et al.*, 2001; Gustavsson and Sathre, 2006; Petersen and Solberg, 2005; Zabalza Bribián *et al.*, 2011). A review and synthesis of numerous international studies on wood products (Sathre *et al.*, 2010) concludes that the manufacturing of wood products requires less total energy, and in particular less fossil energy, than the manufacturing of most alternative materials. Cradle to gate analyses of material production, including the acquisition of raw materials, transportation, and processing into usable products, show that wood products need less production energy than a functionally equivalent amount of metal, concrete or bricks. Frühwald (1996) defines wood as 'low energy building material' since it requires relatively little energy for forestry and wood processing. A meta-analysis of the displacement factors of wood products substituted in place of non wood-materials observes an average displacement factor value of 2.1, meaning that for each tC (tons of Carbon) in wood products, there occurs an average GHG emission reduction of approximately 2.1 tC, which is roughly 1.9 CO_2 emission reduction per m^3 of wood product (Sathre and O'Connor, 2010).

Recent studies also indicate that wood-based wall systems entail 10 – 20 % less embodied energy than traditional concrete systems (Sathre and Gustavsson, 2009; Upton *et al.*, 2008). An Australian study states that significant GHG emission savings are achieved by maximising the use of wood products for two common house designs in Sydney, with the timber maximised design resulting in approximately half the GHG emissions associated with the base design (Ximenes and Grant, 2013).

Moreover, wood is usually considered to be carbon neutral (Hennigar *et al.*, 2008; Pingoud *et al.*, 2010) since it is assumed that the carbon dioxide released in the combustion phase at the end of the product life equals the carbon dioxide absorbed during the growth of a same amount of biomass in forest. In other words the harvested wood in forest can be replaced in a relatively short time through the carbon absorption in forest. Some studies agreed that an active forest management increases the efficacy in the mitigation of climate change (Hennigar *et al.*, 2008; Liu and Han, 2009). There are trade-offs between sequestering C stocks in forests and the climatic benefits obtained by sustainable forest harvesting and using wood products to displace fossil C emissions. A reduced harvesting and wood supply has a temporary positive impact on the C stock in forest; on the other hand wood use, substituting for energy-intensive materials or fossil fuels, can displace fossil C emissions and contribute to GHG mitigation too, and, in addition, wood products sequester C (Pingoud *et al.*, 2010). Trees can be seen as a stock of carbon which has been converted into biomass as the result of photosynthesis. When this biomass is harvested and transformed into wood products, a portion of the carbon contained in the biomass remains fixed until the products decay or are burned. So wood products act like temporary reservoirs to which carbon is transferred (UNFCCC, 2003). Additionally, using wood products at their end of life as substitute energy source, emissions from other sources, such as fossil fuels, could be reduced.

Besides the former reasons, Pajchrowski et al. (2014) report the technological qualities of wood which make its role in the modern economy become more and more important. Among these, it is both light and mechanically strong, it has a good thermal conductivity coefficient, creates a comfortable environment and has good thermal and noise insulation properties.

Improved knowledge of the environmental impacts of the materials and processes associated with productive sectors including the wood-based sector is a key factor in guiding efforts towards green production processes and green markets (Bovea and Vidal, 2004).

1.4. Life Cycle Assessment as a means to evaluate environmental sustainability

To evaluate the environmental impacts produced by building materials the Life Cycle Assessment (LCA) is the internationally recognized and standardized tool. A LCA is the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle. Through the LCA it is possible to quantify the environmental impacts in all the phases of the product supply chain, from the acquisition of the raw materials from the environment, until the production, distribution, use and disposal of the final product (UNI EN ISO 14040, 2006; UNI EN ISO 14044, 2006).

LCA applied to building materials provides the quantitative and comparative values of the environmental impacts of various building technologies (Singh et al. 2011; Zabalda Bribián et al. 2011; Takano et al. 2015).

More than one software for LCA has been developed, one of which is GaBi software ("Ganzheitliche Bilanz," meaning Holistic Balance), developed by PE International.

LCA is an iterative technique. The individual phases of an LCA use results of the other phases. The iterative approach within and between the phases contributes to the comprehensiveness and consistency of the study and the reported results. LCA can assist in identifying opportunities to improve the environmental performance of products at various points in their life cycle, informing decision-makers in industry, government or non-government organizations (e.g. for the purpose of strategic planning, priority setting, product or process design or redesign), the selection of relevant indicators of environmental performance, and marketing (e.g. implementing an ecolabelling scheme, making an environmental claim, or producing an environmental product declaration).

There are four phases in an LCA study:

a) goal and scope definition phase

b) inventory analysis phase,

c) impact assessment phase, and

d) interpretation phase.

The relationship between the phases is illustrated in Figure 1.1.

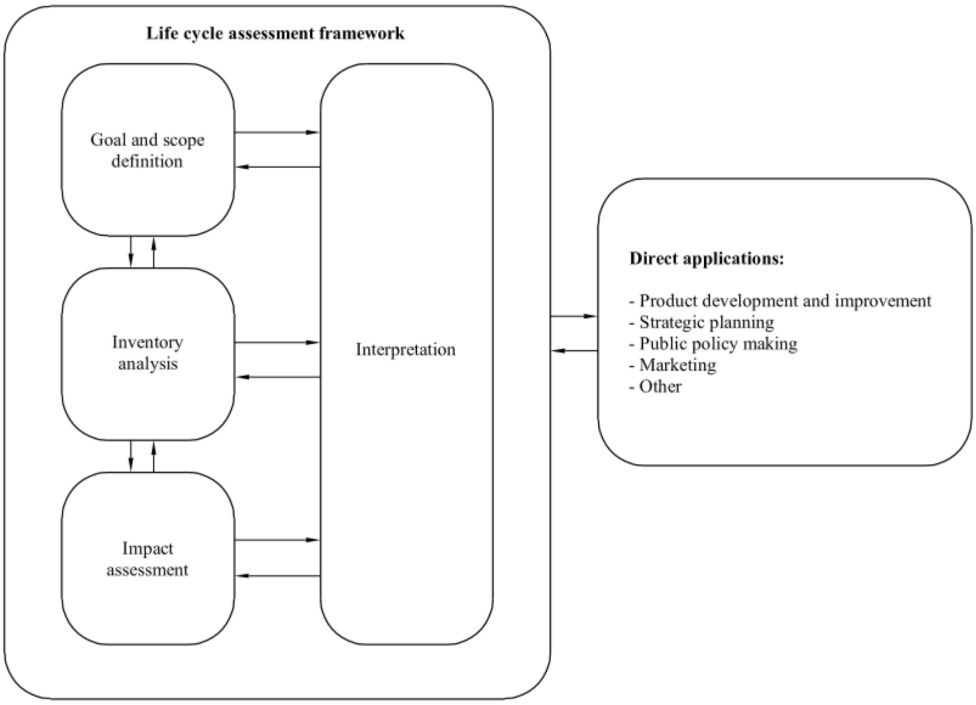

Figure 1.1| Stages of an LCA, from EN ISO 14040

1.4.1. Goal and scope definition

The scope of an LCA depends on the subject and the intended use of the study. It includes the product system to be studied, the functions of the product system or, in the case of comparative studies, the systems; the functional unit; the system boundary; and other specifications of the study.

The system's function and functional unit are central elements of an LCA. Without them, a meaningful and valid comparison especially of products is not possible, as stated by the ILCD Handbook (European Commission, 2010). The functional unit represents the quantified performance of a product system for use as a reference unit for the LCA study. It is the unit of scale or reference on which the LCA results are based, and relates to the given function of the product (Wittstock *et al.*, 2012).

The primary purpose of a functional unit is to provide a reference to which the inputs and outputs are related. This reference is necessary to ensure comparability of LCA results. Comparability of LCA results is particularly critical when different systems are being assessed, to ensure that such comparisons are made on a common basis (UNI EN 14040, 2006). The functional unit has a quantity, a duration and a quality: it names and quantifies the qualitative and quantitative aspects of the function(s) along the questions “what”, “how much”, “how well”, and “for how long” (European Commission 2010; Wittstock *et al.*, 2012).

1.4.2. Life Cycle Inventory

The life cycle inventory analysis phase (LCI phase) is the second phase of LCA. It involves collection of the data necessary. Inventory analysis involves data collection and calculation procedures to quantify relevant inputs and outputs of a product system, to meet the goals of the defined study. The process of conducting an inventory analysis is iterative. As data are collected and more is learned about the system, new data requirements or limitations may be identified that require a change in the data collection procedures so that the goals of the study will still be met. (EN ISO 14040, 2006).

The definition of the goal and scope of the study provide the initial plan for conducting the life cycle inventory phase of an LCA. When executing the plan for the life cycle inventory analysis, the operational steps outlined in Figure 1.2 should be performed (EN ISO 14044,2006).

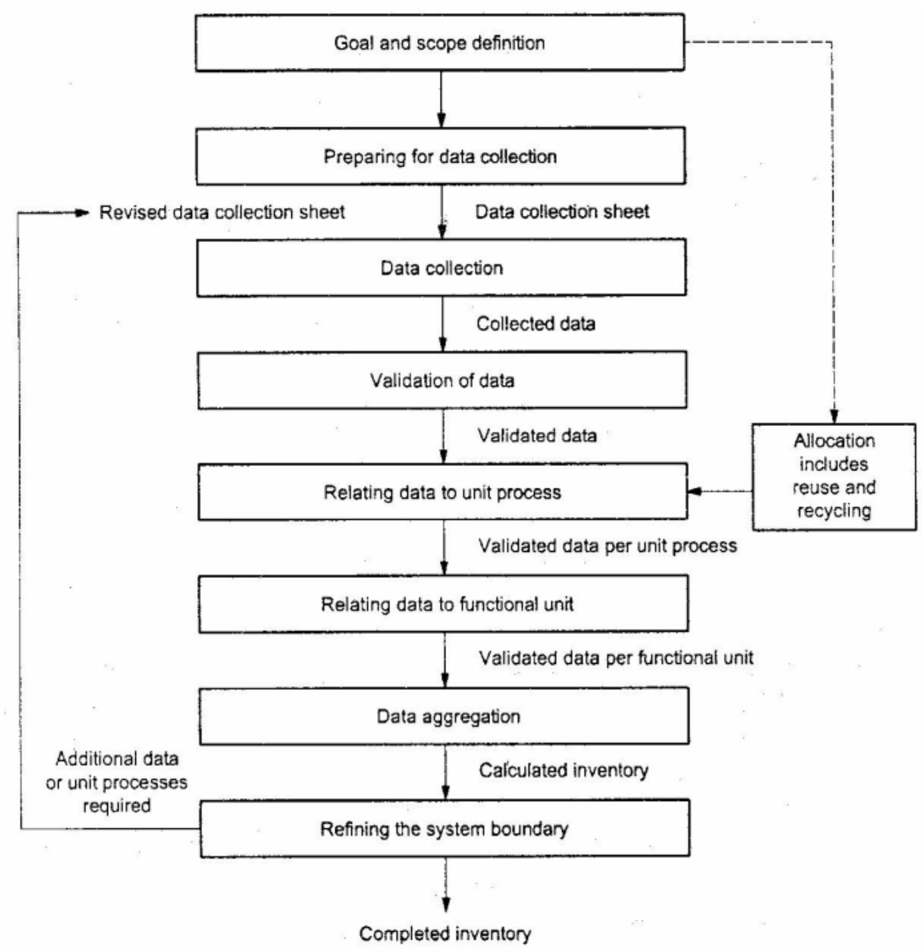

Figure 1.2| Simplified procedure for inventory analysis following EN ISO 14044-2006

The steps of an LCI are (U.S. EPA, 2006):

a) Development of a flow diagram of the processes being evaluated, based on the goal and scope and system boundaries definition;
b) Development of a data collection plan, identifying the required data, data sources and types and preparing a data collection sheet;
c) Collection of data, which requires a combination of research, site-visits and direct contact with experts, as well as the use of a database and LCA software packages;
d) Evaluating and reporting of results.

1.4.3. Life Cycle Impact Assessment and Impact categories

The life cycle impact assessment phase (LCIA) is the third phase of the LCA. It is aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product. In other words, it is the evaluation of potential human health and environmental impacts of the environmental resources and releases identified during the LCI, trying to establish a linkage between the product or process and its potential environmental impacts (U.S. EPA, 2006).

Steps of a LCIA, both described in the U.S. EPA document and in EN ISO 14044 (2006), are:

a) Selection and definition of impact categories: identifying relevant environmental impact categories;

b) Classification: assigning LCI results to the impact categories;

c) Characterization and normalization: modelling LCI impacts within impact categories using science-based conversion factors called characterization factors, to convert and combine the LCI results into representative indicators of impact, expressing potential impacts in ways that can be compared;

d) Grouping: sorting or ranking the indicators (e.g. by location: local, regional, and global);

e) Weighting: emphasizing the most important potential impacts;

f) Evaluating and reporting results.

Impact Categories are the classifications of human health and environmental effects caused by a product throughout its life cycle. The emissions and resources derived from LCI are assigned to each of these impact categories. They are then converted into indicators using factors calculated by impact assessment models. These factors reflect pressures per unit emission or resource consumed in the context of each impact category (European Commission - Joint Research Centre, 2011).

Impact categories for the compartments air, water and soil can be developed through an LCA. As far as the air compartment is concerned, the LCA includes global scale impact categories such as the Global Warming Potential (GWP) and the Ozone Depletion Potential (ODP) and local and regional scale impact categories such as the Photochemical Ozone Creation Potential (POCP) and the Human Toxicity Potential (HTP). According to U.S. EPA’s LCA Principles and Practice (2006) LCI items that contribute to two or more different impact categories their LCA results can be assigned to all impact categories to which they contribute.

“Greenhouse effect” is the warming of the surface of Earth caused by the reflecting of solar radiations operated by Earth’s surface, radiations which are absorbed by greenhouse gases in the troposphere and re-radiated in all directions, including back to earth. In addition to the natural mechanism, the greenhouse effect is enhanced by human activities. This produces an increase of temperature in the lower atmosphere that can lead to climate and environmental changes. Greenhouse gases (GHG), believed to be anthropogenic, include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and chlorofluorocarbons (CFCs) (Schuller *et al.*, 2013). The GWP is calculated in carbon dioxide equivalents (CO_{2eq}), meaning that the greenhouse potential of an emission is given in relation to CO_2. Since the residence time of gases in the atmosphere is incorporated into the calculation, a time range for the assessment must also be specified, usually 100 years.

The second impact category at global level concerns the ozone that is created in the stratosphere by the disassociation of oxygen atoms that are exposed to short-wave UV-light. This leads to the formation of the so-called ozone layer in the stratosphere (15-50 km high). The ODP regards the decomposition of the stratospheric ozone layer that causes an increase in the incoming UV-radiation that leads to impacts on humans, natural organisms and ecosystems. The substances which have a depleting effect on the ozone can essentially be divided into two groups; the CFCs and the nitrogen oxides (NO_X). The ODP for each substance contributing to depletion is given in trichlorofluoromethane equivalents (CFC 11_{eq}).

No matter where the contributing substances are emitted they contribute to the same phenomenon and GWP and ODP impact categories are therefore considered to be global.

At local scale, the LCA takes into account the potential effects of emissions on the photochemical ozone creation and on the human health throughout the POCP and the HTP categories.

Despite playing a protective role in the stratosphere, photochemical ozone production in the troposphere damages vegetation and materials and high concentrations of ozone are toxic to humans. POCP addresses the impacts from ozone and other reactive oxygen compounds formed as secondary contaminants in the troposphere by the oxidation of the primary contaminants Volatile Organic Compounds (VOC) or CO in the presence of NO_x under the influence of light. In LCA POCP is referred to ethylene-equivalents (C_2H_{4eq} or ethene$_{eq}$). It is important to note that the actual troposphere ozone concentration is strongly influenced by the weather and by the characteristics of local conditions.

Finally, Human Toxicity Potential reflects the potential harm of some substances (such as heavy metals) on human health. Assessments of toxicity are based on tolerable concentrations in air, water, tolerable daily intake and acceptable daily intake for human toxicity. For each toxic substance HTPs are expressed using the reference unit: 1.4-Dichlorbenzol-Equivalents (DCB$_{eq}$). The primary route of potential human exposure to this compound is inhalation. It produces various damages on human health and is anticipated to be a carcinogen.

Several methods to calculate these impact categories exist. One of them is the CML 2001 – Apr. 2013 impact assessment method, included in the GaBi software. Once the impact categories are chosen, the software does an automatic classification and characterization based on the LCI results.

CML 2001 – Apr. 2013 methodology was proposed by scientists under the lead of CML (Center of Environmental Science of Leiden University) and is defined for the midpoint approach (PRé, 2014). Midpoint approach, or problem-oriented approach, translates impacts into environmental themes such as climate change, acidification, human toxicity, etc. Endpoint impact category, also known as the damage-oriented approach, translates environmental impacts into issues of concern such as human health, natural environment, and natural resources.Analysis at a midpoint minimizes the amount of forecasting and effect modeling incorporated into the LCIA, thereby reducing the complexity of the modeling and often simplifying communication (U.S. EPA, 2006). For GWP, CML uses the indices published by the IPCC (Intergovernmental Panel on Climate Change), with 100 years time range, as recommended as baseline characterisation method for climate change (Schuller *et al.*, 2013). For ODPCML methodology uses the Ozone Depletion Potentials (ODPs) published by the World Meteorological Organisation (WMO).

1.4.4. Life Cycle Interpretation

Life cycle interpretation is the final phase of the LCA procedure, in which the results are summarized and discussed as a basis for conclusions, recommendations and decision-making in accordance with the goal and scope definition. In this phase it is also possible, as is done in this study, to make a comparative assertion: an environmental claim regarding the superiority or equivalence of one product versus a competing product that performs the same function (EN ISO 14040, 2006).

2. Objectives

With these forewords, the aim of this research is to perform a comparative LCA in order to evaluate the environmental impacts in terms of emissions produced during the construction of a wooden wall and a brick wall, and to determine which of the two systems is the more sustainable towards GHG emissions and other environmental quantities.

Two assumptions will be made for the comparison: (i) the two walls have the same life-cycle time for what concerns raw material acquisition and product manufacturing; (ii) the two walls have the same insulation and energy efficiency properties.

The wooden building system that will be analyzed is the innovative *Massive Holz Mauer* (MHM) wall, which uses aluminium nails instead of adhesives used for traditional glue-lam systems to connect the wooden boards forming the walls. The brick wall will be designed with the same insulation properties as the timber wall to guarantee the comparability. Both walls are intended to be used as exterior walls.

The assessment is performed as a gate-to-gate LCA that considers for both systems the production and supply of the materials needed for the building of the wall.

For both the systems the four impact categories (GWP, ODP, POCP and HTP) are calculated and compared.

3. Materials and Methods

3.1. Product systems

In the following sections details are given about the chosen product systems on which to perform the LCA.

3.1.1. *Massiv Holz Mauer* (MHM) wall overview

MHM is a massive solid wood wall, hence the name *Massiv-Holz-Mauer* in German.

The license application was submitted by the *Massiv-Holz-Mauer* Entwicklungs GmbH at the "Deutsche Institut für Bautechnik" (German Institute for building technologies) in 2012. The tests required for the certification for the product have been conducted in collaboration with the Bauart Konstruktions-GmbH of Lauterbach at the MFPA Leipzig GmbH.

This centre for notifications, endorsements and accreditations has carried out a series of tests to evaluate the performance of the building system. To give some examples, MHM system is able to produce air/wind tightness according to DIN 4180 (German standard regarding thermal insulation and energy economy in buildings). For what concerns fire, a 20.5 cm MHM wall has shown a fire resistance F90B meaning that it can prevent to collapse when on fire for 90 minutes. Usually the requirement for independent houses is class F30B. Moreover, according to the certificate, up to 95 % of the high-frequency rays (mobile communications, television, beam radio etc.) are shielded even in the uncovered raw wall.

Moreover, MHM solid wood slab elements have obtained the European Technical Assessment (ETA) in 2013 passing rigorous tests. An ETA is a document providing information about the performance of a construction product, to be declared in relation to its essential characteristics. This definition is provided in the new Construction Products Regulation (EU/305/2011) entered into force on 1st of July 2013 in all European Members States and in the European Economic Area.

MHM is a pre-manufactured building system characterized by high precision, quickness in construction (6 months turnkey), no use of glue and design flexibility.

According to the ETA definition, MHM wall elements are made of softwood boards which are bonded together with fluted aluminium nails in order to form cross laminated timber (solid wood slab elements). The solid wood slab elements consist of at least five up to fifteen adjacent layers arranged perpendicular to each other. Surfaces are rough, except for the outer surfaces of the outer boards of the wall that may be planed. In the longitudinal direction, the boards are grooved on one side up to a maximum depth of 3 mm: the grooves achieve additional quantities of entrapped air that significantly improve the insulation value (Technical data Massiv-Holz-Mauer). The used wood species is Norway spruce (*Picea abies*) or equivalent softwood.

It is a cost-effective way of building since windows, doors and installation ducts are integrated into the elements.

An interesting aspect is the possibility to use low-grade timber, thus presenting some imperfections like knots, discolouring or small cracks, without affecting the structure. Moreover, the wall gets covered usually with plaster or wood panels. The German standard DIN 4074-1:2012 is applied for the quality requirements definition.

3.1.2. MHM wall construction

MHM walls are built by special computer-controlled units developed for this production by Hundegger (http://www.hundegger.de). The nearly fully automatic production process is divided into three parts: (i) grooving of individual boards, (ii) the production of individual wall panels and (iii) the so-called joinery, i.e. finishing of the wall panel to obtain a ready to install part. Each board is dried to a water content of 14% ±1%, and it is 23 mm thick and from 14 to 26 cm wide. The maximum height of a MHM wall is 3.25 m while the maximum length is 6 m. In detail, the boards are pre-processed with a specially developed cutterhead (Figure 3.1a) which cuts a 3 mm step groove on either side and a series of 3 mm x 3 mm kerfs on one surface of the board. From the formed boards the “Wall Master” (Figure 3.1b) produces raw wall elements varying in sizes and thickness, in which the boards are installed perpendicular (lengthwise and crosswise) and connected with aluminium groove spikes layer by layer. Each board intersection is nailed with two spikes in the greatest possible distance to each other, that is diagonally. This ensures the greatest possible stability. After reaching the desired wall thickness the raw wall element is moved into the CNC-portal processing centre PBA (Figure 3.1c), where the element is formatted and the necessary door and window openings are cut. Also drilling for lifting slings, slots and recesses for heating and sanitary, as well as electrical sockets and other installation preparations are milled into the wall element by computer-controlled tools (Paevere and MacKenzie, 2006). A complete MHM production line (Figure 3.2) can produce about 18,000 m^2 of wall elements per year in single-shift working

Figure 3.1| Hundegger MHM (a) Cutterhead, (b) WallMaster,(c) PBA

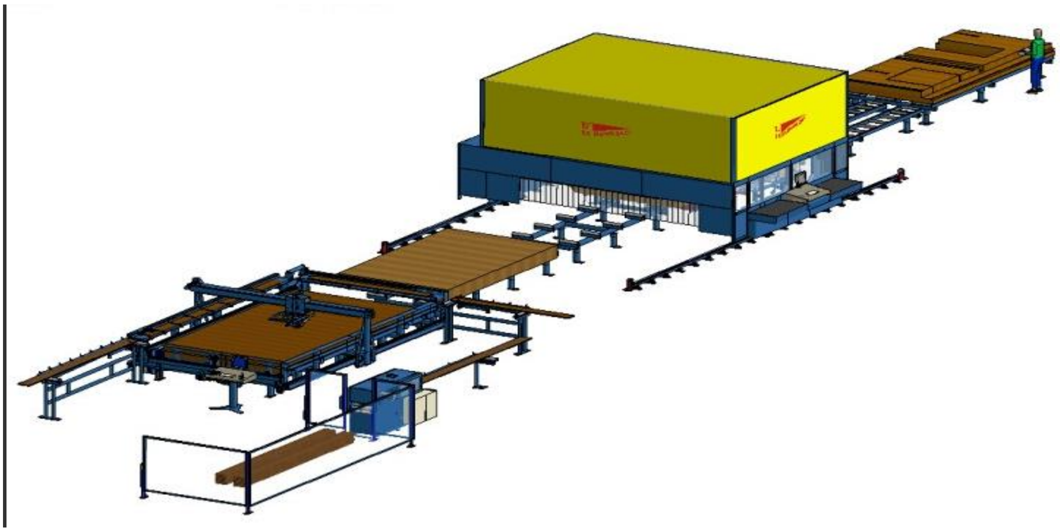

Figure 3.2|Hundegger MHM production line

3.1.3. MHM wall product system

In Italy, the only MHM producer is FBE Woodliving Company set in Castelgomberto (Vicenza). MHM walls can be composed of a different combination of number of plank layers and wood fibre insulation boards thickness. According to FBE, one of the most used external walls is composed of 9 layers of boards, each layer formed by side by side placed 23 mm thick boards . This results in a wooden structure which is 2 mm planed so that the final thickness of it is 20.5 cm. The total thickness of the wall is 28.5 cm.

Two overlapping 40 mm thick wood fibreboards provide insulation to the structure, and a plaster façade is usually added to complete the wall structure.

In detail, the considered MHM frame is formed, from the inside of the house to the outside, by (Figure 3.3):

- plasterboard layer (a);
- 9 grooved board layers, each layer formed by several side by side 23 mm thick boards, connected by aluminium nails (b);
- transpiring geotextile layer (c);
- 2 wood fibreboards (Thermowall and Thermosafe) (d);
- mortar layer (e);
- plaster mesh (f);
- plaster for outer covering (g).

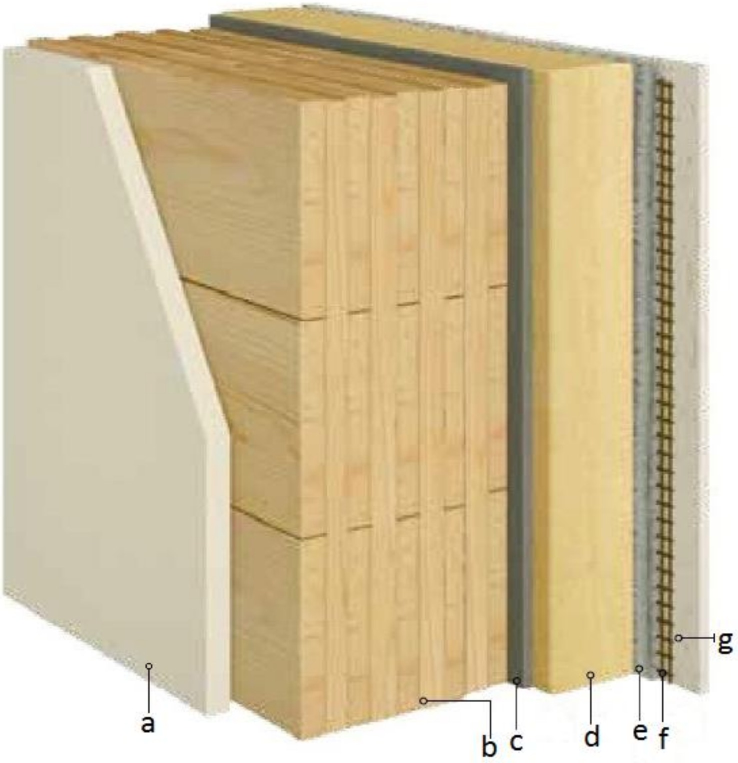

Figure 3.3| Section of the chosen type of MHM wall.3.1.4. Brick wall product system

To understand which traditional brick wall to consider, advice was asked to Arch. Lorenzo Coltro (Viale Roma 15, Vicenza) who works in the same Region as FBE.

According to Arch. Coltro, brick houses are one of the most frequently independent houses built in Veneto Region. In particular, the chosen wall is a one-layer brick wall. It has the following elements, from the inside to the outside (Figure 3.4):

- lime and cement plaster layer (a);
- perforated clay bricks (e.g. Porotherm BIO PLAN 30-25/19,9) + mortar on the horizontal surfaces of the bricks (b);
- insulating panel in extruded polystyrene foam (XPS) (c);
- lime and cement mortar layer (d).

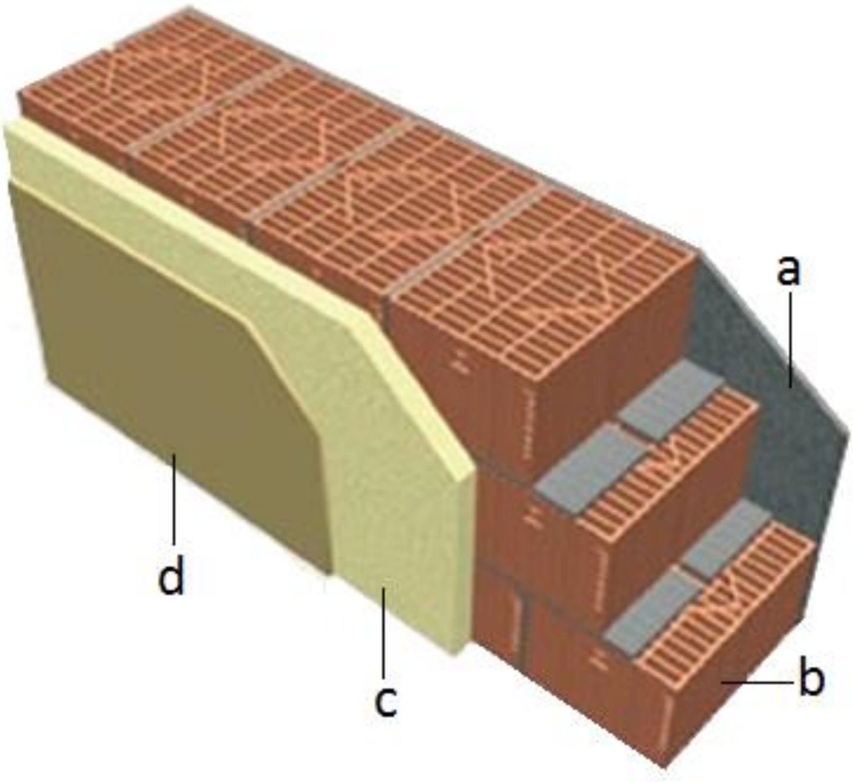

Figure 3.4| Section of the chosen type of brick wall

3.2. Function and functional unit

The main function of a wall structure is to provide a durable protection allowing the creation of a living space, respecting building code requirements. It includes minimal insulation and air-tightness levels to enable the heating of the space at comfortable temperatures, as well as minimum structural resistance, fire protection and moisture management to ensure the durability of the building. The envelope is one of the main parts of the buildings and the external walls directly influence the thermal and environmental performance of the building envelope (Silvestre *et al.*, 2006).

On this basis the chosen functional unit is for both systems 1 m^2 of exterior wall, maintaining its function over 50 years, and ensuring a thermal transmittance (U-value) of 0.21 W/m^2K.

1 m^2 of wall has been chosen because, according to the ILCD Handbook (data, nelle referenze ce ne sono due), comparisons between different materials on a mass – and therefore on volume - basis are meaningless and misleading. Unit of mass or volume of material is inadequate as a functional unit because equal masses or volumes of different materials do not fulfil the same function (Gustavsson and Sathre, 2011). 50 years is the operational duration required for MHM panels by the ETA, and has been assumed the same for the brick wall.

Finally, 0.21 W/m^2K is the thermal transmission of the chosen MHM wall and as a consequence the brick wall is supposed to be designed to have the same insulation property.

3.3. System boundaries

A gate-to-gate LCA is performed to compare both product systems. For a comparative LCA, the system boundaries needs to be the same for both the building systems. A gate –to-gate approach does not take into account the whole supply chain as a cradle-to-grave approach. A cradle-to-grave approach requires a huge amount of primary data that were difficult to collect for this study. For both products the investigated system boundaries are the supply of raw materials and their manufacturing. In the end the building elements are ready to be conveyed at the construction site where the building has to be set up.

Raw material extraction (felling of trees, clay extraction, etc.) and transport are not incorporated within the system boundaries.

As can be seen in Figure 3.5, the system boundaries for the LCA of 1 m2 of MHM include all the processes needed to produce it starting from raw materials manufacturing processes until the assembling of the wall at FBE Woodliving. The wall components construction processes include sawmill process to produce the wooden planks and manufacturing processes of fibreboards and non-wooden elements of MHM wall (plasterboard, aluminium nails, etc.). Process energy consumption and transport process of the different materials to FBE are included in the system boundaries. Energy for assembling of the components at FBE is included. Out of the system boundaries, the ready-made walls will be used to construct a wooden building.

On the other hand, a brick wall is not prefabricated, so no assembling process is needed to be included in the system boundaries (Figure 3.6). The manufactured materials such as bricks or mortar will be assembled out of the boundaries at the building construction site. Thus, no transport to third parties and no assembling energy are considered.

These boundaries have been set because of the lack of data for other life phases, such as raw material extraction, building, operational and disposal phases. It is in any case important to remind that the operational phase of a building produces the widest impact on the environment. Indeed, Ximenes and Grant (2013) deduced from the comparison of timber and non-timber houses that the emissions associated with the extraction, manufacture, transport, use and disposal of materials are significantly lower than operational energy emissions. Also Adalberth et al. performed in 2001 an LCA on four multi-family buildings built in Sweden considering different phases of a building life: manufacturing, transport, erection, occupation, renovation, demolition and removal phase. They noticed that the occupation phase alone accounted for about 70–90% of total environmental impact caused by a building, so they remark that it is important to choose such constructions and installations options which have less environmental impact during its occupation phase.

Concerning the disposal phase**,** Scharai-Rad and Welling (2002) analysed single-family houses constructed in central Europe made with either wood or brick. They considered the utilisation of processing and demolition residues to replace fossil fuels, and found that net GHG emission decreased as the volume of recovered wood increased.

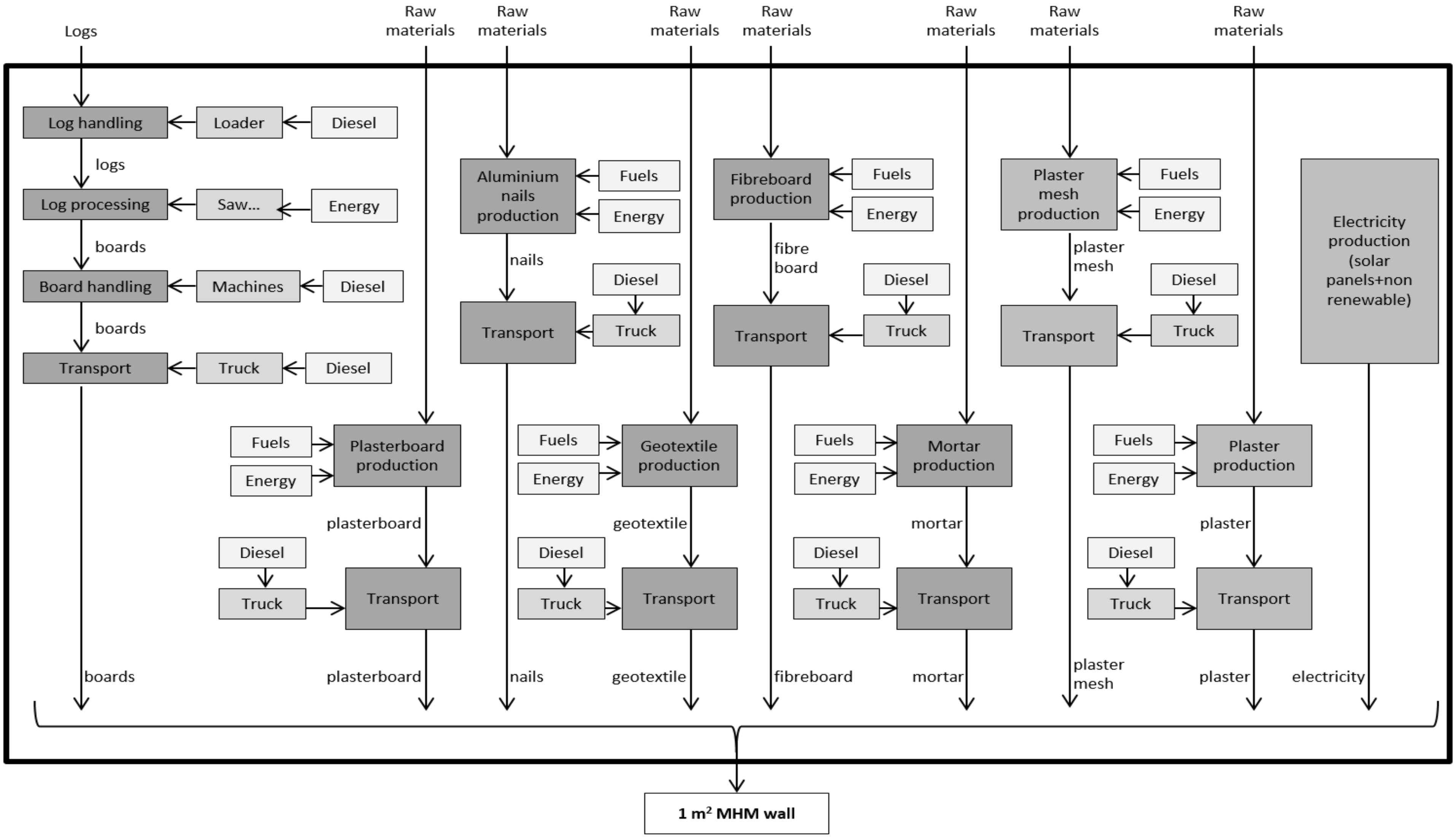

Figure 3.5| Process flow diagram showing the system boundaries of the investigated MHM wall production processes. Note: lubricant inputs are not specified in this process flow.

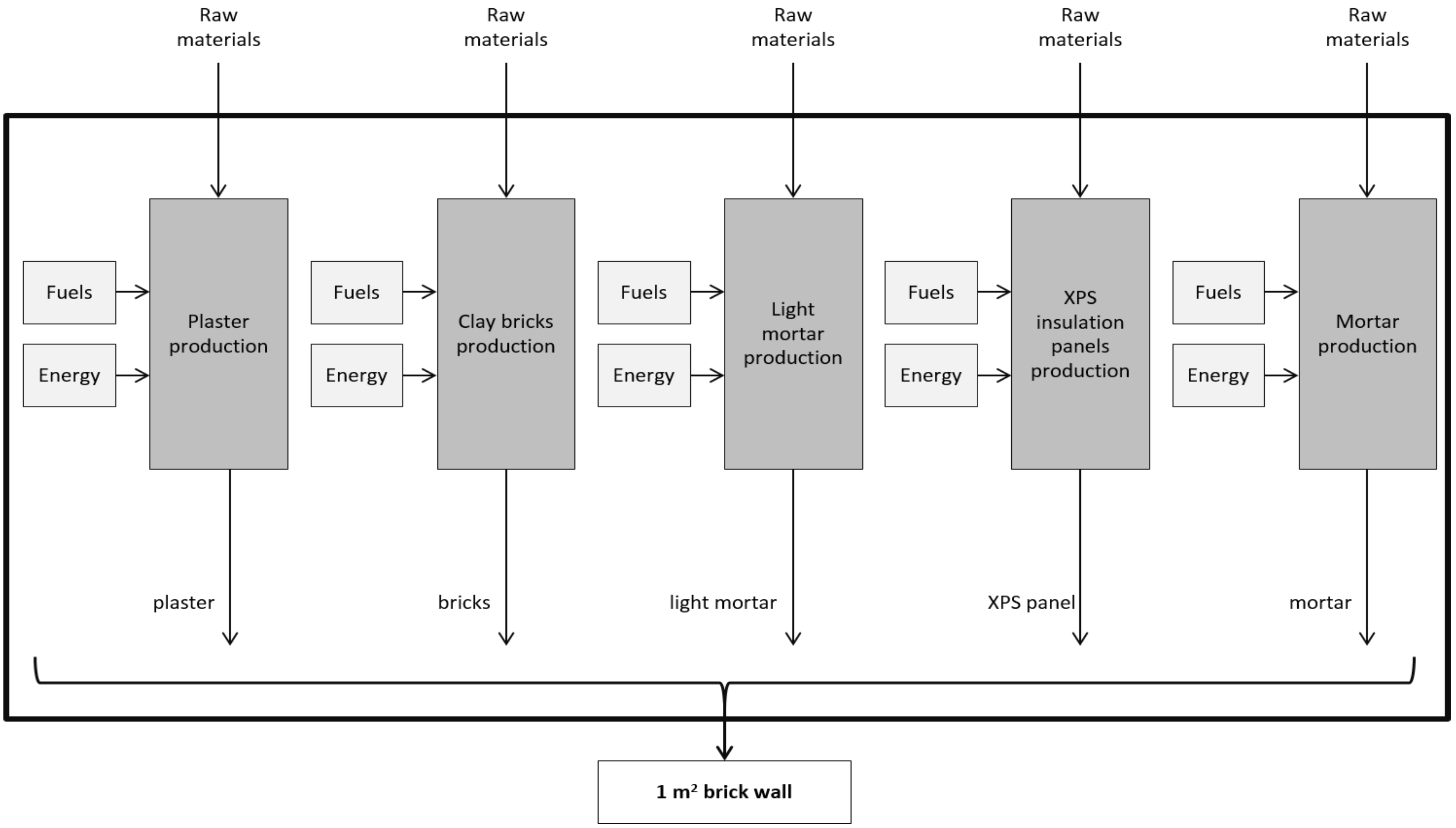

Figure 3.6| Process flow diagram showing the system boundaries of the investigated brick wall production processes.

3.4. Life Cycle Inventory

In the following chapters data and information collected to do the LCI of the two product systems are described. Primary data have been collected mainly for the wooden boards for MHM process production and for the quantities of material and energy needed to build 1 m2 of MHM and of brick wall product systems. On the other hand secondary data have been gathered for the production processes different than board manufacturing and for the emission factors, and have been provided by Ecoinvent database (Frischknecht et al., 2004), integrated in GaBi Software. It is internationally recognized by the scientific community to be one of the most complete database to perform LCA studies.

3.4.1. Data collection for MHM wall

The production of MHM wall frames has been divided into two main phases, each of them further divided in several processes. The two main phases are the sawmill phase, performed at Saviae sawmill and the assembling phase, performed at FBE Woodliving company.

3.4.1.1. Sawmill process and data collection

FBE buys the boards for MHM system either from an Austrian sawmill or from three different sawmills located in Veneto Region. Since the study is focused on the local production, one of the latter has been chosen: Saviane Industria Legnami Dei F.lli Saviane Di Pompeo Srl, set in Puos d'Alpago (BL). It is a family timber industry that provides sawing, processing and storage of sawn wood.

On the 20000 m^2 available surface Saviane company has a computer managed joinery machine working on 5 axes, and a sawmill with two different types of saws: a frame saw and a band saw. MHM planks are produced using the band saw. MHM production was 400 m^3 in 2014, corresponding to the 5% of the total production of sawnwood.

65% of the spruce logs cut in the Saviane sawmill come from the Province of Belluno (Veneto), 30 % from the Friuli-Venezia Giulia, and 10% from Germany. As said before, wood for MHM is usually low-grade timber and comes from the local forests, meaning that there is no need for import. These forests are FSC certified. The logs are bought cut-to-length and not necessary debarked, and transported by a lorry with 46 t load capacity and hydraulic crane to the sawmill yard. These spruce trunks have a water content around 40% when they get sawn, and a density of 631 kg/m3 (Francescato et al., 2009).

With a “Solmec 120 SC” loader the trunks are taken from the yard and brought at the band saw (Figure 3.7). The band saw debarks the trunk and produces raw wooden boards (Figure 3.8). MHM building system requires boards at least 140 mm wide, 23 mm thick and of random length. They are afterwards automatically moved with a belt conveyor towards a trimmer which finishes the boards (Figure 3.9). The bark and the trims are conveyed to a chipper, while the sawdust is withdrawn by a series of aspirators. Both the wooden chips and the sawdust are stocked and sold. The finished boards, still rich in water content, are transferred using one of three available diesel forklifts to a storage yard (Figure 3.10) where they are stocked and kept until they dry in open-air to a 13-14% water content (480 kg/m^3 density, as stated by FBE). The drying requires 4-5 months in the summer.

For what concerns waste products, the only ones produced are the wooden chips from the trims and bark and the sawdust. On average, one raw board is equivalent to 70% of finished board, 22% wooden chips and 8% sawdust. The chips are sold to a biomass power plant in Ospitale di Cadore (BL), while the sawdust is mainly sold to livestock farms.

The transport of the finished product to FBE, that is 166 km far from Saviane sawmill, is done with a 46 t load truck.

Figure 3.7| (a) The sawmill yard and (b) the loader bringing the trunks to the band saw.

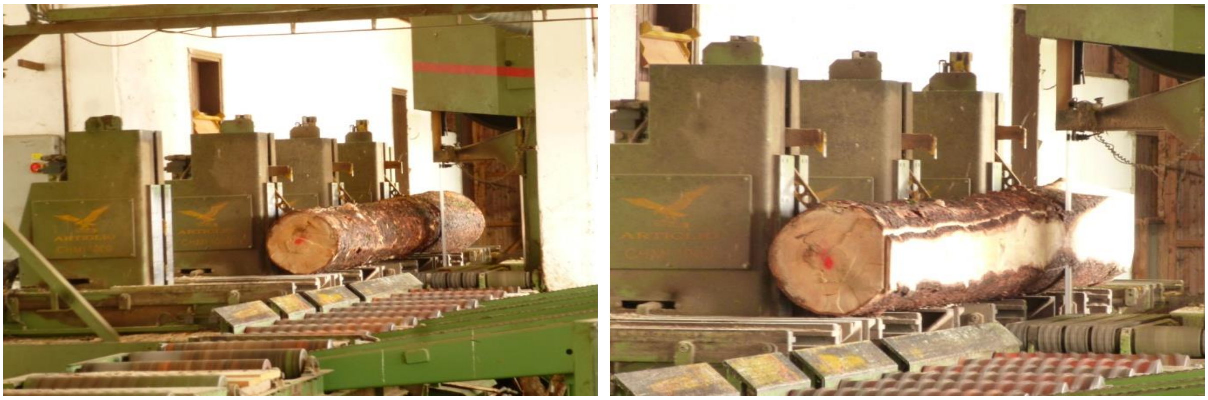

Figure 3.8| (a and b) The band saw cutting the trunks in raw boards.

Figure 3.9| (a) Detail of the belt conveyors system and (b) finished boards exiting the trimmer.

Figure 3.10| (a) Drying-stocking yard and (b) diesel forklift.

Since the functional unit of this LCA study is 1 m^2 of wall, all the collected data has been referred to this unit of measure. Table 3.1 reports the quantity of wood, diesel, electricity and lubricants necessary to Saviane sawmill to produce 1 m^2 of MHM boards.

Table 3.1| Wood, diesel, electricity and lubricants consumption to produce 1 m^2 of MHM boards

Object		**Gross engine horsepower (GHP)**	**Unity of measure**	**Quantity**
Spruce wood		-	m^3	0.033
Electricity	Band saw	75	kWh	0.4
	Trimmer	75	kWh	0.4
	Chipper	60	kWh	0.32
	Belt conveyors	20	kWh	0.1
	Aspiration system	40	kWh	0.22
Diesel	Loader	120	l	0.036
	Forklift 4 t	75	l	0.016
	Forklift 6 t	110	l	0.023
	Forklift 7 t	110	l	0.023
	Lubricant band saw	-	l	0.001
Lubricants	Loader	120	l	0.0007
	Band saw	75	l	$0.5*10^{(-7)}$
	Forklift 4 t	75	l	0.0003
	Forklift 6 t	110	l	0.0005
	Forklift 7 t	110	l	0.0005
Transport		-	tkm	1.86

These quantities will be multiplied by 9 in the final plan since 1 m2 of MHM wall contains 9 board layers, each of 1 m^2 and 23 mm thick.

The wood volume of 1 m^2 is:

$$1\ m^2 * 0.023\ m = 0.023\ m^3$$

of wooden planks, weighing

$$0.023\ m^3 * 480\ kg/m^3 = 11.04\ kg$$

For one raw board entering the trimmer, 70% results in finished board and 30% in waste wood (chips and sawdust).

The percentage of m^3 of MHM planks produced by the band saw per year is 8% of the total production. Data about horsepower and working hours/year of the involved machines have been collected (Table 3.1); the actual power rate of the machines was estimated as 70% of the rated output. Starting from these information, the energy consumption for band saw, trimmer, chipper, belt conveyors and aspiration system to produce 1 m^2 of boards have been calculated.

Diesel consumptions to move the trunks (loader) or 1 m^2 of MHM boards (forklifts) have been determined throughout an equation provided by the "Machine COST calculation tool", a costing model developed for the European Cooperation in Science and Technology (COST) Action FB0902 (Ackerman et al., 2014):

$$Diesel\ consumption\ (l/h) = 0.31\ (l/kWh) * Load\ factor\ (\%) * Engine\ rated\ power\ (kW)$$

where 0.31 l/kWh is a constant which considers the diesel consumption of a motor driven at full power and the specific mass of diesel, and the load factor, which considers that the motor seldom runs at full power, is usually set to 0.4. A small amount of diesel is also used to keep the saw of the band saw lubricated.

The amount of lubricants and motor oil used for the loader, the forklifts and the hydraulic system of the band saw have been estimated using a series of equations that can be found in FAO Forestry Paper 99 (FAO, 1992). In this paper lubricants include engine oil, transmission oil, final drive oil and grease. The consumption rate varies with the type of equipment, environmental working condition (temperature), the design of the equipment and the level of maintenance. In the absence of local data, the lubricant consumption in litres per hour could be estimated as

$$\begin{aligned} Lubricants &= crankase\ oil + transmission\ oil + final\ drivers + hydraulic\ control \\ &= (0.0006 + 0.0003 + 0.0002 + 0.0001) * GHP \end{aligned}$$

where GHP is the gross engine horsepower. For the band saw only the hydraulic control part has been considered: it is an estimation but more precise data about the lubricant needed for a band saw has not been found in literature.

Finally, in GaBi software emissions related to transport are automatically determined by giving as input the tons of transported product per kilometres of transport distance. So, if 1 m^2 of MHM wall plank is considered, first the kilograms are converted in tons (11.04 kg=11.04*10^{-3} t) then the tons are multiplied by the distance (km) as follows:

$$11.04 * 10^{-3} * 166 = 1.86\ tkm$$

where 166 is the distance (km) between Saviane sawmill and FBE company.

3.4.1.2. FBE data collection

FBE Woodliving company is divided in three facilities: one for the offices and two designated to build wooden houses. Indeed, FBE owns the machinery suitable to produce pre-fabricated houses with two different building systems: the more traditional blockhaus and MHM. To assemble MHM walls FBE owns the equipment provided by Hundegger and described in chapter 3.1.2.
Table 3.2 summarizes the amounts of materials needed for 1 m^2 of MHM wall, as stated by FBE. The resulting mass is 128 kg. 10 kWh of electricity are consumed to assembly the wall materials described in Table 3.2.

Table 3.2| Building materials needed for 1 m2 of MHM wall (thickness = 28.5 cm)

Element	Unity of measure	Quantity	Transport distance from FBE (km)	Features
Plasterboard	kg	9.5	200	gypsum plasterboard
Spruce boards	m^2	9	166	water content 13%, density 480 kg/m^3. 9 overlapping layers each 23 mm thick. . Total volume 0.207 m^3 before planing
Aluminium nails	kg	0.7	600	Threaded nails, specially developed for MHM
Transpirant gotextile	kg	0.15	150	-
Insulating fibre board Thermosafe	mm	40	600	density 110 kg/m^3
Insulating fibre board Thermowall	mm	40	600	density 160 kg/m^3
Mortar	kg	6	200	
Plaster mesh	m2	1	200	glass fibre mesh; weight 150 $g/m^{2;}$
Plaster	kg	2.5	200	outer cover of the wall

To produce 1 m^2 of MHM wall 9 layers of 23 mm spruce boards are necessary. The sum of these results is 207 mm thickness, but the outer layer is planed 2 mm, so the wood component of the wall actually measures 205 mm.
As for the volume, this is:

$$1\ m^2 * 0.25\ m = 0.205\ m^3$$

with a density of 480 kg/m^3 (water content 13%). The total amount of wood contained in 1 m^2 of wall is

$$0.205 * 480 = 98.4\ kg$$

Considering these materials, the thermal transmittance of the wall reaches the value of 0.21 W/m^2K. Thermal transmittance, also known as U-value, is the main parameter used to calculate the thermal losses through the walls of a building. It is the rate of transfer of heat (in watts) through one square metre of a structure divided by the difference in temperature across the structure (in Kelvin degrees). The lower the U-value, the better the insulation. It is expressed in W/m^2K. Losses due to thermal radiation, thermal convection and thermal conduction are taken into account in the U-value.

It can be calculated with the following equation (ENEA):

$$U = \frac{1}{R_{si} + \sum \frac{s_i}{\lambda_i} + R_{se}}$$

Where:

R_{si} is the inner surface resistance, equal to 0.13 m^2K/W (according to DIN ISO 6946);

R_{se} is the external surface resistance, equal to 0.04 m^2K/W (according to DIN ISO 6946);

s_i/λ_i is the thermal resistance (R) of each layer of different material present in the wall. Thermal resistance is the ability of a material to prevent the passage of heat. It is the thickness of the material in metres (s) divided by its thermal conductivity (λ).

FBE company provided the U-value for the wall considered in this study.

Secondary data provided by Ecoinvent database have been used in GaBi LCA model, since the collection of primary data relative to the production processes, besides wooden boards, would have required a too large amount of time.

3.4.2. Data collection for brick wall

Arch. Coltro provided some documents useful to understand the specific composition of the brick wall (Porotherm bricks and Styrodur isulant panels technical data sheets).

As has been done for MHM, secondary data from Ecoinvent database have been used to consider the production process of building materials in the LCA model.

To make the two products comparable, the brick wall has been chosen with the same U-value than the timber wall. A thermal transmittance of 0.21 W/m^{2}K can be reached thanks to a thickness of 40 cm, obtained with the materials reported in Table 3.3, which shows the quantities necessary to build 1 m^2 of brick wall. The mass of this frame is 313 kg.

Table 3.3| Building materials needed for 1 m2 of brick wall (thickness = 40 cm)

Element	**Thickness (m)**	**Quantity (kg)**	**% on total mass**	**Thermal conducivity λ (W/mK)**	**Features**
Lime and cement plaster	0.015	27	9%	1	decor plaster; density 1800 kg/m^3
Clay bricks	0.3	276.6	88%	0.14	20 pored bricks per m^2
Mortar between bricks	0.001	1.65	1%	0.281 (included in λ of the wall)	light mortar; density 1000 kg/m3
Insulating panels	0.09	2.4	1%	0.036	Extruded polystyrene (XPS); density 30 kg/m3
Lime and cement mortar	0.003	5.4	2%	1	mortar for outer cover; density 1800 kg/m3

The solution of the equation for the U-value of the chosen brick wall is:

$$U = \frac{1}{0.13 + \frac{0.015}{1} + \frac{0.3}{0.14} + \frac{0.09}{0.036} + \frac{0.003}{1} + 0.04} = 0.21\ \mathrm{m^2K/W}$$

3.5. Software for LCA

GaBi 6 software has been used to perform the gate-to-gate Life Cycle Assessment, to generate the emissions factors and to analyse the relative contribution of the wooden and concrete buildings supply chain to emissions. GaBi 6 is a software package developed by PE International designed for analysing the environmental impact of products and services over their whole life cycle.

3.6. LCA modelling with GaBi 6

Once the data collection is complete, the system modelling through GaBi 6 software can done. This starts with the transfer of collected data into GaBi software system (Schuller *et al.*, 2013). GaBi 6 is organised into hierarchic modules: plans, processes and flows. These are formed into modular units.

The fundamental basis of modelling using GaBi 6 is the object type flow. A GaBi 6 flow is a representative of an actual product, intermediate, material, energy, resources or emission flow. The flows form a process. Plans (or plan systems) are used in GaBi 6 to structure the processes in a product system. Essentially, plans are the “process maps” which visually depict a stage or sub-stage in the system and help to understand the technical reality behind the system (Figure 3.11).

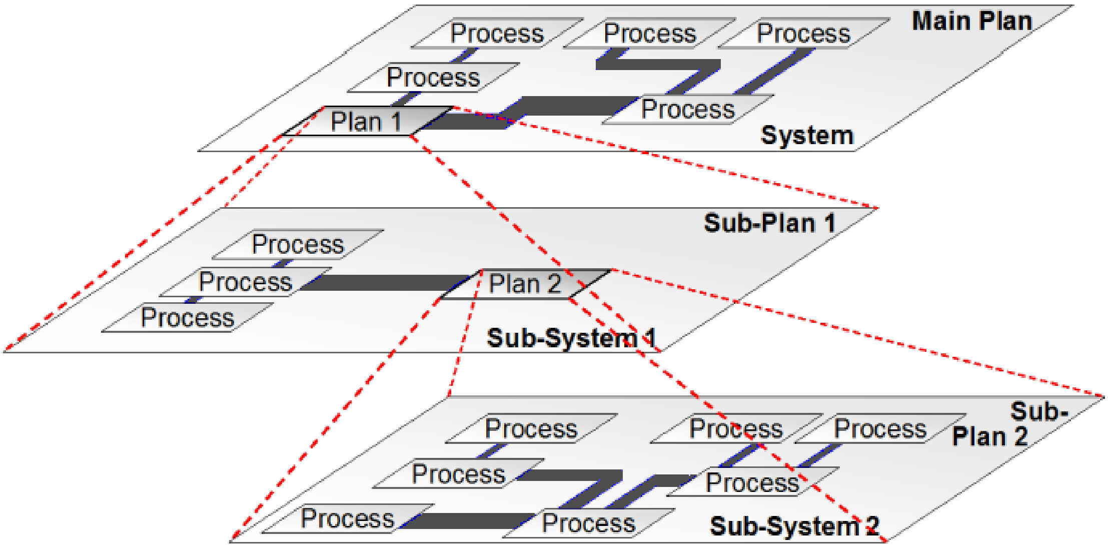

Figure 3.11| Hierarchical structure of the processes and plans (Schuller et al., 2013)

Missing data is a common problem of LCA. This can happen due to unavailability of data or missing access to data. There is no standard rule for this problem as each case should be analysed separately; Schuller et al. (2013) suggest that the estimation of missing processes in GaBI database can be solved with an estimation based on similar processes or technologies.

3.6.1. MHM wall LCA model

The MHM wall LCA model is shown in Figure 3.12. The quantities of materials and transport distances are specified in Table 3.2 and Table 3.3. The plan is reported in the way data are modelled in GaBi software. In the final assembling process the amount of wood in 1 m^2 of MHM wall (9 m^2 = 98.4 kg) and all other material requirements relative to the functional unit are specified, and emissions deriving from the sawmill process and from all other production processes are correctly quantified by the software.

The plans and processes from Ecoinvent database used to prepare the model are described in detail in the Tables below; it is specified when estimations had to be made due to lacks in the database.

Abbreviations from GaBi software used in this study:

- IT: Italian average
- CH: Swiss average
- RER: European average

Table 3.4 to Table 3.7 describe flow and processes carried out in the sawmill phase of the production process.

Starting from the sub-plan “Log handling” (Table 3.4), this contains the diesel and lubricant amounts related to the loader and the material flow of logs. The plan describes the moving of the logs from the sawmill yard to the band saw with the loader.

The “Log processing” sub-plan (Table 3.5) includes the sawing and trimming of the boards as well as the chipping of waste wood and aspiring of sawdust.

“Boards handling” sub-plan (Table 3.6) considers the movement of MHM boards from the sawing process to the drying yard and from here to the lorry that is to take them to FBE.

“Boards transport” (Table 3.7) is merely the transport of MHM sawnwood from Saviane sawmill to FBE company.

Table 3.8 to Table 3.15 describe flows and processes modellized for MHM building elements different than wood. The datasets associated to these processes in Ecoinvent database from the reception of raw materials at the factory gate to the storage of the final products at the factory. For what concerns the transport of these materials, since it is not known which kind of lorries are used, it was supposed that for transport distances below 200 km a 16-32 ton capacity lorry is used, while for greater distances a truck with more than 32 metric ton carrying capacity is used.

For aluminium nails (Table 3.9) and plaster mesh (Table 3.13) production specific processes have not been found so a necessary simplification has to be done. Indeed, more general processes have been chosen from Ecoinvent database: respectively “aluminium product manufacturing” and “Glass fibre production”, both European average. The aluminium product manufacturing dataset in Ecoinvent encompasses manufacturing processes to make a semi-manufactured product into a final product, so the phase of primary aluminium production is not accounted. For the glass fibre, it is the specific phase of plaster mesh production from glass fibre that is not included, since the dataset is a gate to gate inventory for the production of glass fibre.

Some issues had to be solved for what concerns the insulation wood fibreboard panels. In MHM wall two types of panels with slightly different densities are used. In Ecoinvent just one process which produces soft fibreboards is suitable, producing fibreboards with an intermediate density (140 kg/m^3) between Thermosafe (110 kg/m^3) and Thermowall (160 kg/m^3). Ecoinvent intermediate process has therefore been considered. The production is a Swiss average because neither an European nor Italian average were not available in the database.

FBE company has solar panels installed of the rooftop of their facilities: the solar energy is used for production (Table 3.15).

The outputs from the plans “Boards transport”, “Plasterboard”, “Aluminium nails”, “Geotextile”, “Thermosafe+Thermowall”, “Mortar”, “Plaster mesh”, “Plaster” and “Electricity” are connected in the main plan to the MHM wall assembling plan.

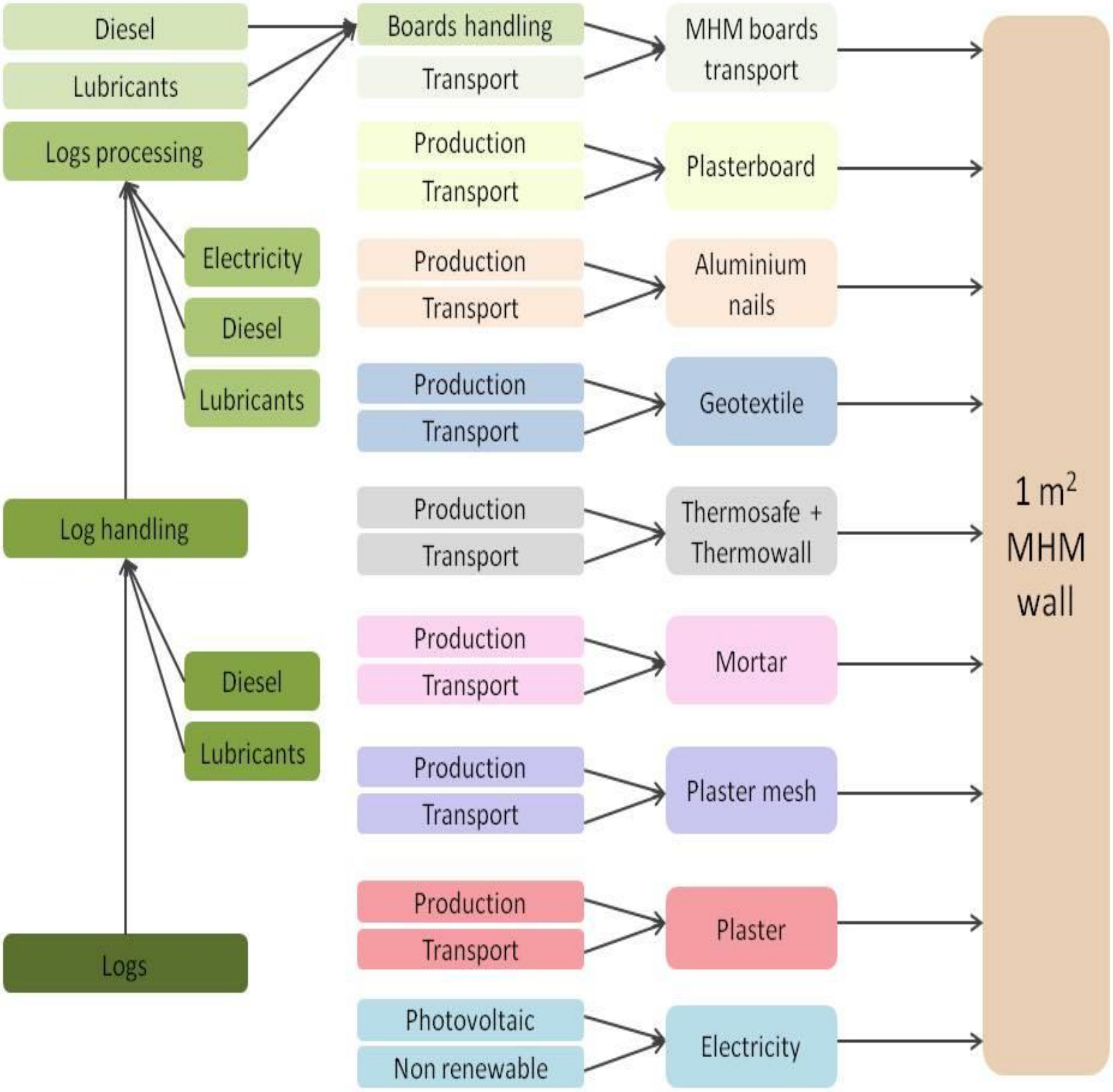

Figure 3.12| Final GaBi LCA plan for MHM wall

Table 3.4| Flows and processes for the sub-plan “Log handling”.

Plan: Log handling	
Inputs	**Related process**
Logs on the sawmill yard	-
Diesel for the loader	Europe without Switzerland: diesel production, low-sulphur
Lubricant for the loader	RER: lubricating oil production
Output	
Logs ready to be processed	

Table 3.5| Flows and processes for the sub-plan “Log processing”.

Log processing	
Inputs	**Related process**
Log handling (plan)	-
Diesel to lubricate the band saw	Europe without Switzerland: diesel production, low-sulphur
Lubricants for the hydraulic system of the saw	RER: lubricating oil production
Electricity for saw, trimmer, chipper, band conveyors and aspiration system	IT: electricity, high voltage, production mix
Output	
1 m^2 MHM boards	

Table 3.6| Flows and processes for the sub-plan “Boards handling”.

Plan: Boards handling	
Inputs	**Related process**
Log processing (plan)	-
Diesel for the forklifts	Europe without Switzerland: diesel production, low-sulphur
Lubricant for the forklifts	RER: lubricating oil production
Output	
1 m2 MHM boards on drying yard	

Table 3.7| Flows and processes for the sub-plan “Boards transport”.

Plan: Boards transport	
Inputs	**Related process**
Boards handling (plan)	-
Transport	RER: transport, freight, lorry >32 metric ton, EURO5
Output	
Transported boards at FBE company	

Table 3.8| Flows and processes for the sub-plan “Plasterboard”.

Plan: Plasterboard	
Inputs	**Related process**
Plasterboard production	CH: gypsum plasterboard production
Transport	RER: transport, freight, lorry 16-32 metric ton, EURO5
Output	
Plasterboard at FBE company	

Table 3.9| Flows and processes for the sub-plan “Aluminium nails”.

Plan: Aluminium nails	
Inputs	**Related process**
Aluminium nails production	RER: aluminium product manufacturing, average metal working
Transport	RER: transport, freight, lorry >32 metric ton, EURO5
Output	
Aluminium nails at FBE company	

Table 3.10| Flows and processes for the sub-plan “Geotextile”

Plan: Geotextile	
Inputs	**Related process**
Geotextile production	RER: fleece production, polyethylene
Transport	RER: transport, freight, lorry 16-32 metric ton, EURO5
Output	
Geotextile at FBE company	

Table 3.11| Flows and processes for the sub-plan “Thermosafe+Thermowall”.

Plan: Thermosafe+Thermowall	
Inputs	**Related process**
Insulation fibreboard panels production	CH: fibreboard production, soft, from wet processes
Transport	RER: transport, freight, lorry >32 metric ton, EURO5
Output	
Insulation fibreboard panels at FBE company	

Table 3.12| Flows and processes for the sub-plan “Mortar”.

Plan: Mortar	
Inputs	**Related process**
Mortar production	CH: cement mortar production
Transport	RER: transport, freight, lorry >32 metric ton, EURO5
Output	
Mortar at FBE company	

Table 3.13| Flows and processes for the sub-plan “Plaster mesh”.

Plan: Plaster mesh	
Inputs	**Related process**
Plaster mesh production	RER: glass fibre production
Transport	RER: transport, freight, lorry >32 metric ton, EURO5
Output	
Plaster mesh at FBE company	

Table 3.14| Flows and processes for the sub-plan “Plaster”.

Plan: Plaster	
Inputs	**Related process**
Plaster production	CH: cover plaster production, mineral
Transport	RER: transport, freight, lorry >32 metric ton, EURO5
Output	
Plaster at FBE company	

Table 3.15| Flows and processes for the sub-plan “Electricity”.

Plan: Electricity	
Inputs	**Related process**
Photovoltaic electricity production	IT: electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted
Electricity from non renewable sources production	IT: electricity, high voltage, production mix
Output	
Electricity at FBE company	

3.6.2. Brick wall modelling

The brick wall modelling (Figure 3.13) was simpler than the wooden wall since all the production processes of the building material where taken from Ecoinvent.
In the following table (Table 3.16) the main plan (corresponding in this case to the final plan) is described in detail with the processes used in GaBi software. Again, Ecoinvent datasets refer to gate to gate inventories of the production.

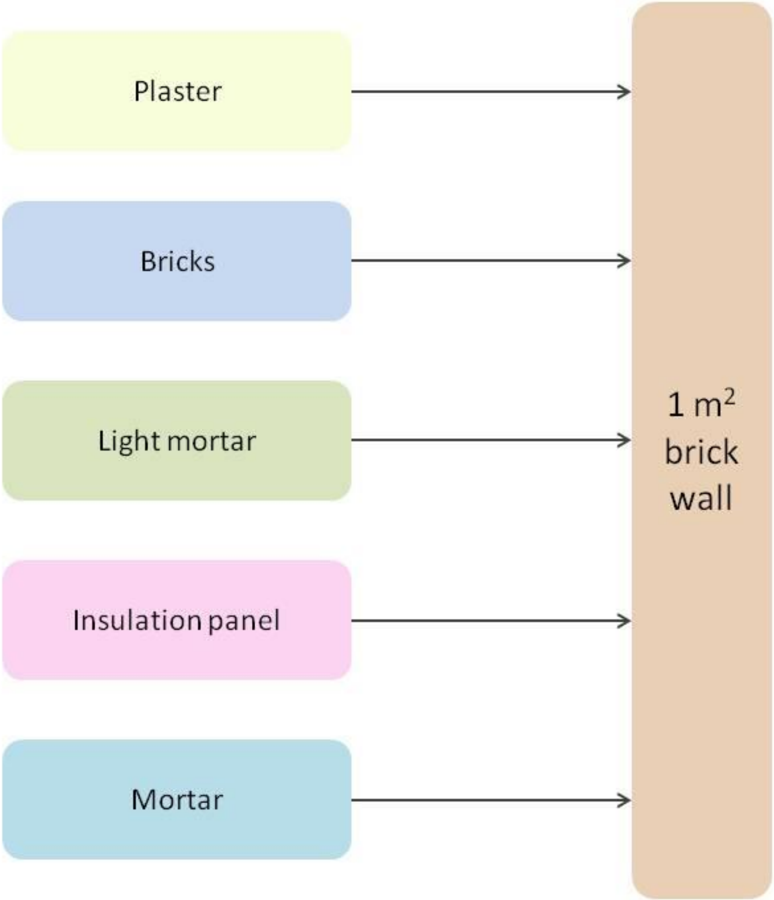

Figure 3.13| Final GaBi LCA plan for brick wall.

Table 3.16| Flows and processes for brick wall model.

Plan: Brick wall	
Inputs	**Related process**
Plaster	CH: cover plaster production, mineral
Bricks	RER: brick production
Light mortar	CH: light mortar production
Insulation panel	CH: polystyrene foam slab for perimeter insulation
Mortar	CH: cement mortar production
Output	
1 m^2 brick wall	

3.7. Impact categories

The four impact categories used to assess and characterize the environmental impact of the two types of wall are described in chapter 1.4.3. These are the Global Warming Potential (GWP) and Ozone Depletion Potential (ODP) at global scale and Photochemical Ozone Creation Potential (POCP) and Human Toxicity Potential (HTP) at regional scale. The results obtained in each impact category will be expressed in terms of their reference gas, thus using a common characterization factor: GWP in terms of carbon dioxide equivalents (CO_{2eq}), the ODP in terms of trichlorofluoromethane equivalents ($R11_{eq}$), the POCP in terms of ethylene equivalents ($Ethene_{eq}$) and the HTP in dichlorobenzene equivalents (DCB_{eq}).

The environmental impacts will be calculated utilizing the CML 2001 – Apr. 2013 impact assessment method incorporated within GaBi. Note that normalization has not been done in this study, where normalization is a technique for changing impact indicator values with differing units into a common, unitless format by dividing the value(s) by a selected reference quantity (U.S. EPA, 2006).

The time frame for the assessment of the global warming impact is 100 years, as recommended by the PAS 2050 standard.

3.8. Displacement factor calculation

A displacement factor can express the efficiency of using wood instead of some other material to reduce net greenhouse gas (GHG) emission, by quantifying the amount of emission reduction achieved per unit of wood use (Sathre and O'Connor, 2010). The displacement factor is calculated as the difference in emission divided by the amount of additional wood used, in this case, in the MHM wall. A displacement factor (DF) can be calculated in many units of measure, e.g. units of tC of emission reduction per tC in wood product. In this study it is calculated as tCO_{2eq} emission reduction per t of oven-dry wood product. The equation is:

$$DF = \frac{GHG\ brick - GHG\ MHM}{Wood\ mass\ MHM - Wood\ mass\ brick}$$

Where GHG brick and GHG MHM are the GHG emission resulting from the use of the brick wall and MHM wall alternatives respectively, expressed in tCO_{2eq}, and Wood mass MHM and Wood mass brick are the amounts of wood mass contained in either of the two alternatives, expressed in t oven-dry wood. The amount of wood contained in the brick wall is clearly null.

4. Results and discussion

4.1. LCIA for MHM wall

The results of the LCA of MHM wall production processes are summarized in Table 4.1.
In terms of GWP, the production of 1 m^2 of MHM emits 32.631 kg CO_{2eq}. The main contributing processes are: the sawmill process (33%), the fibreboards manufacturing (23%) and the electricity production for the final assembling of the wall (15%). The emissions related to the assembling energy are nearly totally due to the non renewable electricity production. Information about emissions for single sub-processes in the soft fibreboard production from wet process are not available, since the pre-prepared process from Ecoinvent database has been used. However it is likely that the high emissions are caused by the heating of the water for the pulping phase and for the drying of the panels. Out of the sub-processes of the sawmill, which produced,10.738 g CO_{2eq} ,it is the log processing which causes 82% of the emissions: this amount is again caused by the electricity production mix.
ODP of MHM is 3.936 mg $R11_{eq}$. The main processes influencing this results are again the fibreboards manufacturing, energy production and the sawmill phase, yet in this case ODP emission are more equally distributed between the sub-processes of the sawmill.
POCP, resulting in 14.018 g $Ethene_{eq}$, is mainly caused by the same processes as above but in this case the aluminium manufacturing for the nails is also affecting heavily this impact category, producing 14% of POCP gases.
HTP shows a slightly more uniform distribution of emissions between the processes, with electricity contributing to 9%, glass fibre plaster mesh and fibreboards manufacturing contributing to 15%, sawmill processes 17% and aluminium manufacturing 32%.
While it is difficult to suggest improvements to reduce emissions connected to the soft fibreboard, plaster mesh and aluminium manufacturing, measures could be taken to reduce sawmill and assembling-related emissions. In both cases a larger amount of renewable energy could be used instead of electricity from non renewable sources; FBE could improve its photovoltaic panels system for this purpose. If the totality of the 10 kWh needed to assemble 1 m^2 of wall would be from photovoltaic source, GWP emissions related to electricity would decrease by 84% and overall GWP emissions for MHM would decrease by 2%.

Table 4.1| (a) Specific and (b) relative contributions of MHM wall production process to GWP, ODP, POCP, HTP for the production of 1m2 of wall.

MHM wall					
(a) Specific contributions		**GWP** (kg CO_{2eq})	**ODP** (mg $R11_{eq}$)	**POCP** (g $Ethene_{eq}$)	**HTP** k(g DCB_{eq})
Total		32.631	3.936	14.011	9.251
Plasterboard		3.062	0.267	1.218	0.714
Sawmill process	**sawmill total**	10.738	1.855	4.587	1.604
	log handling	0.169	0.193	0.257	0.035
	log processing	8.856	1.067	2.963	0.990
	board handling	0.287	0.328	0.440	0.059
	tran sport	1.426	0.267	0.927	0.519
Aluminium screws		3.168	0.157	1.906	2.944
Geotextile		0.412	0.008	0.439	0.056
Insulation fibre board		7.560	0.890	3.189	1.429
Light mortar		1.958	0.089	0.530	0.244
Plaster mesh		0.372	0.033	0.191	1.364
Plaster		0.389	0.036	0.187	0.089
Electricity		4.973	0.602	1.762	0.806
(b) Relative contributions		**GWP**	**ODP**	**POCP**	**HTP**
Total		100.00%	100.00%	100.00%	100.00%
Plasterboard	**% on total, of which**	9.38%	6.78%	8.70%	7.72%
	plasterboard	89.39%	77.99%	85.94%	79.49%
	transport	10.61%	22.01%	14.06%	20.51%
Sawmill process	**% on total, of which**	32.91%	47.12%	32.74%	17.33%
	log handling	1.57%	10.39%	5.61%	2.17%
	log processing	82.47%	57.53%	64.59%	61.75%
	board handling	2.68%	17.69%	9.59%	3.70%
	board transport	13.28%	14.39%	20.21%	32.38%
Aluminium nails	**% on total, of which**	9.71%	3.99%	13.61%	31.83%
	aluminium	98.87%	95.75%	98.78%	99.56%
	transport	1.13%	4.25%	1.22%	0.44%
Geotextile	**% on total, of which**	1.26%	0.21%	3.14%	0.61%
	poliethylene	99.07%	91.72%	99.54%	96.91%
	transport	0.93%	8.28%	0.46%	3.09%
Insulation fibre board	**% on total, of which**	23.17%	22.61%	22.76%	15.45%
	soft fibreboard	92.44%	87.98%	88.35%	85.43%
	transport	7.56%	12.02%	11.65%	14.57%
Mortar	**% on total, of which**	6.00%	2.25%	3.78%	2.64%
	cement mortar	94.78%	78.42%	87.48%	84.79%
	transport	5.22%	21.58%	12.52%	15.21%
Plaster mesh	**% on total, of which**	1.14%	0.83%	1.36%	14.75%
	glass fibre	99.31%	98.53%	99.13%	99.93%
	transport	0.69%	1.47%	0.87%	0.07%
Plaster	**% on total, of which**	1.19%	0.92%	1.33%	0.96%
	plaster	89.08%	78.07%	85.19%	82.63%
	transport	10.92%	21.93%	14.81%	17.37%
Electricity	**% on total, of which**	15.24%	15.29%	12.58%	8.71%
	photovoltaic	4.67%	5.47%	10.14%	34.22%
	non renewable	95.33%	94.53%	89.86%	65.78%

It is noticeable that for all impact categories and for all materials needed to build 1 m^2 of MHM it is the production process which accounts for the bigger percentage of emissions, and not the transport, even though the transport distances are sometimes considerable (e.g. 600 km for aluminium nails and fibreboards).

The wooden boards transport contributes to GWP with 1.426 kg CO_{2eq} while the fibreboards transport produces 0.572 kg CO_{2eq}, fibreboards 0.325 kg CO_{2eq} and the other materials transport vary between 0.102 and 0.003 kg CO_{2eq}. The higher value for the wooden boards is to attribute to the greater mass of wood than of the other materials that is needed for 1 m^2 of MHM. The sawmill is located 186 km from FBE Woodliving company where the MHM assembling takes place and the wooden planks are transported by truck. Other transport means are not suitable for a such a short distance. In any case emissions related to transport would increase if the sawnwood for MHM was bought further away, meaning that the local production chain must be encouraged in order to keep them as low as possible. Considering all the production processes and the associated environmental impacts the only way to improve even more the environmental performance of the MHM system would be to improve industrial processes in an emission reduction perspective. It is clearly a complex issue, and specific strategies and guidance may be given only after specific and more detailed studies.

4.2. LCIA for brick wall

Table 4.**2** shows the environmental impacts in terms of GWP, ODP, POCP and HTP associated to the manufacturing of 1 m^2 of traditional brick wall. Among the production processes, the brick manufacturing causes the highest emissions in every impact category, followed by the polystyrene foam slab production. The final value for GWP brick wall production is 83.644 kg CO_{2eq} and brick and polystyrene manufacturing are respectively nearly 82% and 12% of the total. ODP is 6.895 mg $R11_{eq}$, of which brick production represents the 90%. Total POCP is 40.158 g Ethene$_{eq}$ and brick manufacturing is 74% of this emission value while polystyrene production is 20%. Finally, of total 18.638 kg DCB_{eq} of HTP , brick manufacturing produce 90% of emissions.

This time transport processes for the materials were not included because the bricks and the other materials are not assembled at a third-part company: they are ready to be brought at the building site without further manufacturing.

Table 4.2| (a) Specific and (b) relative contributions of the brick wall production process to GWP, ODP, POCP, HTP for the production of 1m2 of wall.

Brick wall				
(a) Specific contributions	**GWP** (kg CO_{2eq})	**ODP** (mg $R11_{eq}$)	**POCP** (g Ethene$_{eq}$)	**HTP** (kg DCB_{eq})
Total	83.644	6.895	40.158	18.638
Cover plaster manufacturing	3.747	0.306	1.718	0.796
Brick manufacturing	68.371	6.181	29.845	16.586
Light mortar manufacturing	0.563	0.022	0.154	0.087
Polystyrene foam slab manufacturing	9.687	0.324	8.138	1.016
Cement mortar manufacturing	1.276	0.061	0.302	0.154
(b) Relative contributions	**GWP**	**ODP**	**POCP**	**HTP**
Cover plaster manufacturing	4.48%	4.44%	4.28%	4.27%
Brick manufacturing	81.74%	89.65%	74.32%	88.99%
Light mortar manufacturing	0.67%	0.33%	0.38%	0.46%
Polystyrene foam slab manufacturing	11.58%	4.70%	20.26%	5.45%
Cement mortar production	1.53%	0.88%	0.75%	0.83%
Total (%)	100.00%	100.00%	100.00%	100.00%

4.3. Comparison of MHM and brick wall

Figure 4.**1** shows the overall impact of the MHM production process is compared to the brick wall production process: the wooden building system shows a better environmental performances for all analyzed impact categories than the traditional one. The GWP of the brick wall (83.644 kg CO_{2eq}) is more than double than the GWP of MHM (32.631 kg CO_{2eq}), and the same happens for the POCP category: 40.158 g $Ethene_{eq}$ for the brick wall and 14.011 g $Ethene_{eq}$ for MHM. ODP and HTP are respectively 43% and 50% lower for the MHM wall (ODP 3.936 mg $R11_{eq}$, HTP 9.251 kg DCB_{eq}) in comparison to the brick wall (ODP 6.895 mg $R11_{eq}$, HTP 18.638 kg DCB_{eq}).

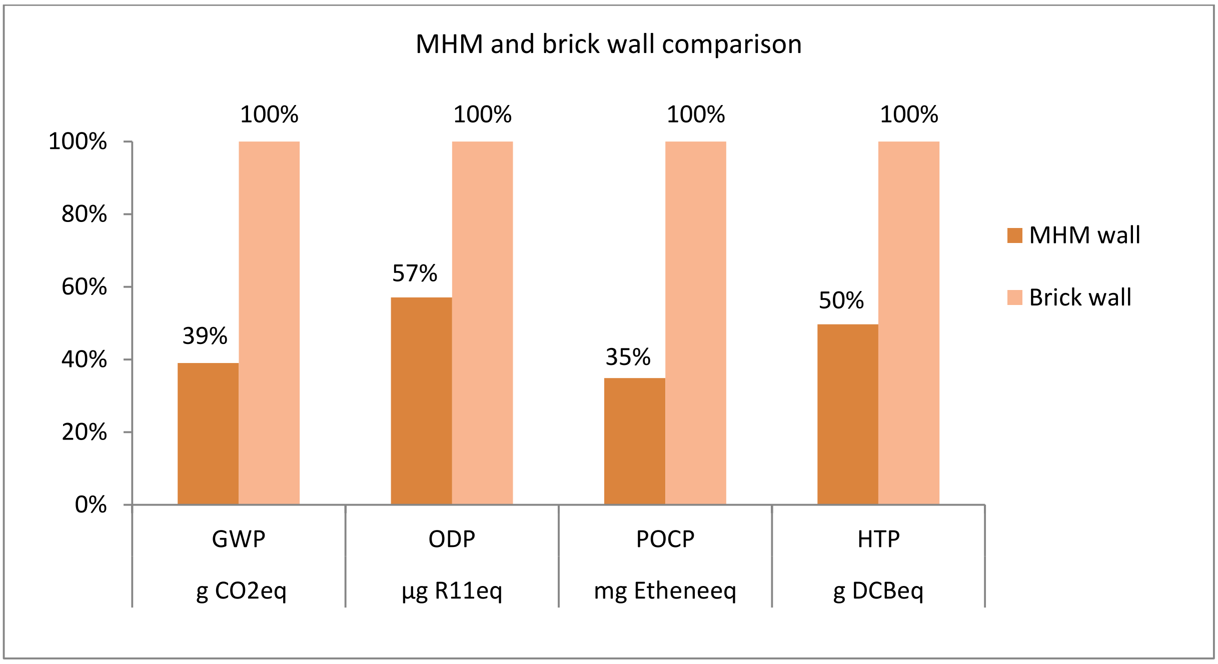

Figure 4.1| MHM and brick wall production processes comparison in terms of relative environmental impacts for the impact categories GWP, ODP, POCP, HTP.

To better understand the contributions to the four impact categories of the production of 1 m^2 of MHM and brick wall, Table 4.3| Contributions to emissions of chemicals for the production of 1m2 of MHM and brick wall. The values are referred to the emissions after characterization ("Characterization" column) and before characterization ("Inventory" column).4.3 shows the list and values of the chemicals emitted. The two columns "Characterization" and "Inventory" represent respectively the results after and before characterization (the phase of the LCA which attributes the impact of different chemicals in terms of a reference gas). The chemicals are sorted by their values after characterization for MHM system, in decreasing order. Note that in Ecoinvent long-term emissions are defined as emissions occurring more than 100 years after present.

Table 4.3| Contributions to emissions of chemicals for the production of 1m2 of MHM and brick wall. The values are referred to the emissions after characterization ("Characterization" column) and before characterization ("Inventory" column).

	MHM wall		**Brick wall**	
Classification	**Characterization**	**Inventory**	**Characterization**	**Inventory**
GWP	**kg CO_{2eq}**	**kg**	**kg CO_{2eq}**	**kg**
Emissions to air (total)	**32.631**	**30.216**	**83.644**	**78.799**
Carbon dioxide	25.193	25.193	76.775	76.775
Carbon dioxide (biotic)	4.940	4.940	1.834	1.834
Methane	1.890	0.076	4.581	0.183
Nitrous oxide (laughing gas)	0.311	0.001	0.204	0.001
Methane (biotic)	0.190	0.008	0.180	0.007
Group NMVOC to air: Halogenated organic emissions (1)	0.073	1.28E-05	0.024	7.79E-06
Sulphur hexafluoride	0.034	1.51E-06	0.047	2.04E-06
Long term to air (Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113)	7.15E-06	1.17E-09	1.05E-06	1.71E-10
ODP	**mg $R11_{eq}$**	**mg**	**mg $R11_{eq}$**	**mg**
Emissions to air (total)	**3.936**	**2.614**	**6.895**	**6.873**
Group NMVOC to air: Halogenated organic emissions (2)	3.934	2.612	6.894	6.873
Long term to air (Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113)	0.001	0.001	1.71E-04	1.71E-04
POPC	**g $Ethene_{eq}$**	**g**	**g $Ethene_{eq}$**	**g**
Emissions to air (total)	**14.011**	**5222.892**	**40.158**	**697.054**
Group NMVOC to air (total), of which	6.468	19.037	24.427	65.785
Halogenated organic emissions (3)	0.002	0.053	5.29E-06	1.84E-04
Others (4)	6.466	18.984	24.427	65.785
Sulphur dioxide	3.920	81.669	5.783	120.475
Nitrogen oxides	1.735	61.961	4.364	155.846
Carbon monoxide	1.011	37.456	0.101	160.794
Carbon monoxide (biotic)	0.377	4939.550	4.341	3.726
Methane	0.454	75.598	1.099	183.229
Methane (biotic)	0.046	7.619	0.043	7.198
Sulphur oxides	4.99E-05	0.001	2.77E-05	0.001
Hydrocarbons (unspecified)	8.67E-06	7.65E-05	5.96E-06	5.25E-05

continua

continua

	MHM wall		Brick wall	
Classification	**Characterization**	**Inventory**	**Characterization**	**Inventory**
HTP	**kg DCB_{eq}**	**kg**	**kg DCB_{eq}**	**kg**
Emissions to air (total)	**9.251**	**0.348**	**18.638**	**0.865**
Heavy metals to air (5)	4.757	2.10E-04	5.709	0.286
Organic emissions to air (group VOC), of which	2.268	0.014	3.274	2.41E-04
Group NMVOC: Polycyclic aromatic hydrocarbons (PAH)	1.727	8.66E-06	0.818	0.060
Group NMVOC: Halogenated organic emissions (6)	0.021	5.36E-05	0.030	5.36E-06
Other NMVOC emissions (7)	0.520	0.014	2.426	1.09E-06
Hydrocarbons (unspecified)	1.34E-09	7.65E-08	9.21E-10	0.060
Inorganic emissions to air (8)	1.655	0.147	9.131	5.25E-08
Long term to air (9)	0.418	4.00E-04	0.449	0.428
Particles to air	0.153	0.186	0.075	0.091
Dust (> PM10)	0.138	0.168	0.049	0.060
Dust (PM2,5 - PM10)	0.006	0.008	0.011	0.014
Dust (PM2.5)	0.008	0.010	0.014	0.017
Silicon dust	1.66E-04	2.03E-04	1.48E-04	1.80E-04
Pesticides to air	4.09E-08	6.78E-08	2.81E-08	4.53E-09

(1) Tetrafluoromethane, R 116 (hexafluoroethane), R 114 (dichlorotetrafluoroethane), R 22 (chlorodifluoromethane), Halon (1301), Perfluoropentane, Halon (1211), R 113 (trichlorotrifluoroethane), R 134a (tetrafluoroethane), R152a (difluoroethane), R 23 (trifluoromethane), R 12 (dichlorodifluoromethane), Carbon tetrachloride (tetrachloromethane), Carbon tetrachloride (tetrachloromethane), R 124 (chlorotetrafluoroethane), Chloromethane (methyl chloride), Dichloromethane (methylene chloride), 1,1,1-Trichloroethane, R 11 (trichlorofluoromethane), Methyl bromide

(2) Halon (1301), Halon (1211), R 114 (dichlorotetrafluoroethane), R 113 (trichlorotrifluoroethane), R 22 (chlorodifluoromethane), Carbon tetrachloride (tetrachloromethane), R 12 (dichlorodifluoromethane), Chloromethane (methyl chloride), R 124 (chlorotetrafluoroethane) 1,1,1-Trichloroethane, R 11 (trichlorofluoromethane), Methyl bromide

(3) Tetrachloroethene (perchloroethylene), Dichloromethane (methylene chloride), Trichloromethane (chloroform), Chloromethane (methyl chloride), 1,1,1-Trichloroethane

(4) NMVOC (unspecified), Pentane (n-pentane), Butane, Hexane (isomers), Propane, Alkane (unspecified), Xylene (dimethyl benzene), Ethene (ethylene), Toluene (methyl benzene), Ethane, Heptane (isomers), Formaldehyde (methanal), Propene (propylene), Benzene, Acetic acid, Methanol, Ethyl benzene, Acetaldehyde (Ethanal), Cumene (isopropylbenzene), Xylene (meta-Xylene; 1,3-Dimethylbenzene), Ethanol, Acetone (dimethylcetone), Butanone (methyl ethyl ketone), Xylene (ortho-Xylene; 1,2-Dimethylbenzene), Ethine (acetylene), Ethylene acetate (ethyl acetate), Propionic acid (propane acid), Styrene, Propionaldehyde, Isopropanol, Methyl tert-butylether, Formic acid (methane acid), 3-Methylpentane, Isoprene, 1-Propanol, 1-Pentene, iso-Butanol, Butadiene, 1-Butanol, 2-Methyl-2-butene, Methyl formate, Methyl acetate, Diethyl ether, Cyclohexane (hexahydro benzene)

(5) Arsenic, Chromium (+VI), Nickel, Antimony, Cadmium, Vanadium, Copper, Selenium, Molybdenum, Cobalt, Thallium, Chromium (unspecified), Lead, Mercury, Zinc, Tin, Hydrogen arsenic (arsine)

(6) Polychlorinated dibenzo-p-dioxins (2,3,7,8 - TCDD), Hexachlorobenzene (Perchlorobenzene), Tetrachloroethene (perchloroethylene), Vinyl chloride (VCM; chloroethene), Carbon tetrachloride (tetrachloromethane), Pentachlorophenol (PCP), Dichloroethane (ethylene dichloride), Trichloromethane (chloroform), Dichloromethane (methylene chloride), Pentachlorobenzene, 1,1,1-Trichloroethane, 2,4-Dichlorophenol, Dichlorobenzene (o-DCB; 1,2-dichlorobenzene), Methyl bromide

(7) Benzene, NMVOC (unspecified), Ethylene oxide, Propylene oxide, Acrolein, Formaldehyde (methanal), Ethene (ethylene), Toluene (methyl benzene), Ethyl benzene, Xylene (dimethyl benzene), Phenol (hydrox benzene), Butadiene, Xylene (meta-Xylene; 1,3-Dimethylbenzene), Xylene (ortho-Xylene; 1,2-Dimethylbenzene), Styrene

(8) Hydrogen fluoride, Nitrogen oxides, Barium, Sulphur dioxide, Beryllium, Hydrogen chloride, Ammonia, Carbon disulphide, Hydrogen sulphyde, Sulphur oxides

(9) Chromium VI, Arsenic, Nickel, Vanadium, Copper, Beryllium, Selenium, Cadmium, Cobalt, Molibdenum, Barium, Lead, Particulates > 10 um, Particulates > 2.5 um and < 10um, Particulates < 2.5 um, Zinc, Antimony, Mercury, Hydrogen sulfide, Tin

4.3.1. GWP

Carbon dioxide is the main contributor to GWP, with 30.133 kg CO_2 for MHM and 78.609 kg CO_2 for the brick wall. Main sources of non-biotic carbon are fossil fuel combustion in industrial processes and for electricity production; transport is a minor contributor. Biogenic carbon is emitted in minor quantity and less for brick wall production. Biogenic carbon for brick wall production is lower (1.834 kg CO_2) since no wood biomass is involved in its production, while for MHM biogenic CO_2 (4.939 kg CO_2) is mainly related to the fibreboards production. The method of evaluation of the biogenic emissions is still object of discussion at international level because they are often assumed equal to the carbon sequestered in forest and neglected. Based on international standards and guidelines, the biogenic carbon dioxide is not accounted in LCA studies (carbon neutrality assumption) or is reported separately (Pierobon *et al.*, 2015). In this study the second option has been chosen.

Methane has a GWP of 25 for a time horizon of 100 years (IPCC, 2007), and is indeed the third emission gas that is produced both for MHM (1890.95 kg) and brick wall building system (4.581 kg). It derives from natural gas and petroleum systems from industries: methane emissions for the brick wall are mainly caused by brick and polystyrene slabs production, while for MHM the main methane emitting processes are electricity from non-renewable sources and aluminium working. The amount of nitrous oxide (N_2O) and sulphur hexafluoride (SF_6) emissions contributing to GWP derive from industrial activities and combustion and are comparable between the two processes. On the other hand, halogenated gases (chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), hydrochlorofluorocarbons (HCFCs), perfluorocarbons (PFCs)) emissions are higher for MHM because of the aluminium manufacturing.

4.3.2. ODP

As has been said, OPD for MHM production process is 60% of OPD for the brick wall. Halogenated organic emissions are 3.934 mg $R11_{eq}$ for the former and 6.894 mg $R11_{eq}$ for the latter. Halon is the emission which mostly contribute to the total halogenated gases in both cases; it is particularly high for brick production (3.472 mg $R11_{eq}$ of Halon 1211 and 2.143 mg $R11_{eq}$ for Halon 1301). Chemicals having an influence on the ozone depletion are emitted in a very small quantity in terms of absolute values: they have a high ozone depletion potential. For example, Halon 1211 has an ODP of 5.3 and Halon 1301 of 16 (WMO, 2007).

4.3.3. POCP

POCP shows the maximum difference in emissions between MHM and brick product systems. In both cases, NMVOCs (non-methane volatile organic compounds) produce the largest fraction of ethane equivalent emissions. The 14.011 g Ethene_{eq} of MHM are caused in particular by electricity production (4.719 g Ethene_{eq}), the industrial processes of aluminium nails (1.883 g Ethene_{eq}) and fibreboards manufacturing (3.189 g Ethene_{eq}). On the other hand it is again the brick production process which contributes the most to 24.427 g Ethene_{eq} of NMVOC formation for the brick wall. For most of the other chemicals with POCP (sulphur dioxide, nitrogen oxides, non biogenic carbon monoxide and methane), emissions for MHM wall are inferior to those relative to the brick wall (Table 4.3| Contributions to emissions of chemicals for the production of 1m2 of MHM and brick wall. The values are referred to the emissions after characterization ("Characterization" column) and before characterization ("Inventory" column).). For what concerns sulphur oxides and unspecified hydrocarbons, emissions are similarly low.

4.3.4. HTP

Finally, HTP is for brick wall production process double (18.638 kg DCB_{eq}) than MHM production (9.251 kg DCB_{eq}) . Heavy metals play an important part in HTP: for MHM 4.757 kg DCB_{eq} are nearly half of the total emissions and for the brick wall nearly a third with 5.709 kg DCB_{eq}. Emissions of heavy metals to air are related to secondary aluminium industry (U.S. EPA, 1995) as well as to brick manufacturing (U.S. EPA, 1997). Chromium (+VI), Arsenic, Nickel, Cadmium and Copper are some of the most pollutant heavy metals and have a great impact on HTP despite the low mass share. In decreasing order for both MHM wall and brick wall, VOCs, inorganic emissions such as hydrogen fluoride and nitrogen oxides, long term to air emissions and particles (mainly dust larger than PM10), also contribute to HTP. This impact category includes dust particles and silicon dust, with 0.075 kg DCB_{eq} for the brick wall and 0.153 kg DCB_{eq} for MHM, where emitted particles are mainly PM>10 and caused by aluminium manufacturing (0.115 kg DCB_{eq}).

4.4. Displacement factor

Considered that 1 m^2 of MHM wall contains 98.4 kg at 13% of water content (density of 480 kg/m3), that corresponds to 97.1 kg (0.0971 t) of oven-dry wood, and that GHG emissions for 1 m^2 MHM wall are 32.63 kg CO_{2eq} (0.0326 t CO_{2eq}), while GHG emissions for 1 m^2 of brick wall are 83.64 kg CO_{2eq} (0.0836 t CO_{2eq}), the solved equation for the DF is:

$$DF = \frac{GHG\ brick - GHG\ MHM}{Wood\ mass\ MHM - Wood\ mass\ brick} = \frac{0.0836\ tCO_{2eq} - 0.0326\ tCO_{2eq}}{0.0971\ t - 0} = 0.53\ tCO_{2eq}/t$$

This means that for each t of wood used to build a wall in MHM instead of bricks, 0.53 t CO_{2eq} are avoided emissions. This value is low if compared to the results of Sathre and O'Connor (2010), who found in their meta-analysis of greenhouse gas displacement factors of wood product substitution an average value of 3.9 t CO_{2eq} emission reduction. Yet the authors assert that the displacement factors vary widely between the 21 case-studies, due to differences in system boundaries between studies.

It is possible to quantify the reduced emissions in building a whole house with MHM system. To build a 100 m^2 house, 40 m^3 of wood are necessary (source: FBE), equal to 18.95 t of oven-dry matter. As a consequence, considering the system boundaries used in this study (not including the in-site building emissions) the emissions avoided are:

$$18.95\ t * 0.53 tCO_{2eq}/t = 9.82 tCO_{2eq}$$

for 100 m^2 of MHM house.

4.5. Discussion

These results are congruent with studies which have the purpose of compare wood and different building materials which find wood to be the most environmentally sustainable building material. It is though remarkable that most studies on this topic compare steel or concrete instead of brick walls or houses to wooden walls or houses. Among studies which consider bricks for building, Goverse *et al*, (2001) compared four house type models with increasing quantities of wood. Comparing the building materials of traditional Dutch brick house to the total-wood house, a reduction in CO_2 of almost 50% has been proved technically possible. Monteiro and Freire (2012) performed an LCA on seven buildings with different exterior walls in Portugal. Comparing the traditional brick wall to the wood frame house, both having similar global thermal coefficients, they too found reductions in GWP for the construction phase of the wooden wall, considering material production and transportation, using the wooden wall of approximately 50%.

In an application of value-focused thinking, Hassan (2004) investigated three exterior wall types: masonry, concrete and timber. The functional unit he chose for the LCA is 1 m^2 of wall with U-value 0.2 W/m^2K. Although also in this case brick and timber wall designs are different from those here analyzed, again the wooden wall proved to be the best option in environmental perspective. In a case study of life-cycle CO_2 emissions of a 137 m^2 single family house built in Austria either with a brick or wood frame, Kram *et al* (2001) determined emissions of 18 tC for the materials production of the wood version and 27 tC for the brick version. In this case, the wooden house emissions are one third lower of those attributed the brick house. Again, specifications about the boundaries and sections of the walls are not given. On the other hand, Marcea and Lau (1992) calculated the energy and CO_2 cost of similar in performance residential buildings, finding that the brick assembly emitted 1.9 times more of the wooden assembly.

In the present study the results show that the wooden wall emits nearly 60% less CO_2 than the brick wall, so the statement of wood construction being less CO_2 emitting than brick construction is confirmed. Yet this case study is not directly comparable to the above cited studies because of the differences in system boundaries, functional unit (whole house and 1 m^2 of wall) or for the variability in the brick wall and especially wooden wall designs, that usually are not even specified.

As last remark, in Goverse's et al. article (2001) it is also shown that substitution of the traditional building materials by wood leads to large reductions in the weight of houses, which could substantially contribute to dematerialization in the construction sector. The difference of weight is high also between MHM wall and brick wall, with the former being about 60% lighter than the latter.

5. Conclusions

In this study a LCA has been performed to assess the emissions to air caused during the production of a *Massiv-Holz-Mauer* (MHM) wooden wall building elements. The results have been compared to the LCA of a traditional brick wall building materials to determine which of the two building systems has the lowest environmental impacts. The LCA has been set up as a gate-to-gate analysis, adopting as functional unit 1 m^2 of wall with thermal transmittance value 0,21 W/m^2K for both products. The system boundaries included all the manufacturing processes needed to build 1 m^2 of wall and the storage of finished building elements at the factories.

The impact categories considered have been Global Warming Potential and Photochemical Ozone Creation Potential at global scale and the Ozone Depletion Potential and Human Toxicity Potential at local scale. For all of the four impact categories MHM wall construction has been proven to produce less emissions. GWP (37%) and POCP (32%) represented respectively the 37% and 32% of traditional wall emissions, while ODP and HTP were respectively 57%, and 50% of the emissions related to the brick wall building materials production.

For MHM, the most contributing processes to GWP and POCP were the log processing into, the fibreboards manufacturing, plasterboard and aluminium nails manufacturing. The energy production for the final assembling of the wall also caused a remarkable share of emissions. ODP was even more influenced by emissions from the whole sawmill and again from fibreboards and electricity production. To these, in HTP category, aluminium nails production is added as one of the more harmful to the environment processes. On the other hand, for what concerns the brick wall production, for all impact categories it is the brick manufacturing that accounts for the majority of emissions.

A displacement factor of 0.53 t CO_{2eq} per t of oven-dried wood for MHM building system used in place of the analyzed brick wall has been calculated in the defined system boundaries conditions.

It should be noted that some simplifications have been adopted to create the models with GaBi software. It would be useful to further analyze the simplified processes (e.g. aluminium nails, plaster mesh for MHM) to produce a more precise model of the MHM wall using primary data.

Furthermore, it would be interesting to perform an LCA on a whole MHM-built house rather than on 1 m^2 of wall. In this case, a complete LCA would comprise all life-cycle phases to have an overview of the actual environmental advantages given by the wooden house. This would result in a cradle-to-grave LCA, where raw material extraction (i.e., considering forest operations for MHM), in-site building phase, operational phase and disposal phase are also assessed. It could be interesting in further studies to evaluate a cascade-approach method for the timber used in MHM system, with wood recycled when and where possible (e.g. to build new houses), and at its last stage of life used as biofuel and burned. Moreover, it could be possible to calculate the carbon offsetting in forest, analyzing data from local Forest Management Plan. This means evaluating in which percentage the carbon emissions produced during the life time of the wooden house can be offset by the growing forest sustainably managed.

Acknowledgements

I would like to thank FBE Woodliving company and the owner Giovanna Fongaro for making this study possible by sharing the data about their production and the knowledge about building with wood.

I am also grateful to Saviane Legno sawmill and in particular to Luciano and Paolo Saviane for having devoted their to me time during the data collection.

I would also like to aknowledge Arch. Lorenzo Coltro for his important contribution to my work.

I wish to express my gratitude to my parents Marleen and Giuliano who allowed me to reach this achievement and that have taught me those values which I consider the most important.

I thank Sofia, because together we discovered indissoluble brotherly love.

My sincere thanks go also to Gabriele, who accompanies me every day with his infinite kindness and patience.

I am thankful to Jennifer, for being one of my safe havens.

To Elena and Claudia, unforgettable firends; to Giulia and Sofia, "le Buone"; to Federica, because new friendships are no less important; to Denise and Valentina, my *ukes* also outside the *tatami.*

I would like to thank my fellow graduate students who have made these five years unforgettable, and Christian, that has always been there.

I am grateful to Michael and Francesca, teachers, yes, but above all friends.

My heartfelt thanks go finally to all those people who have given me the privilege to be a part of their special acquaintances.

Thanks to all pf you for sharing experiences, skills and emotions: you made me infinitely rich.

References

Adalberth K, Almgren A, Petersen EH. 2001. Life-cycle assessment of four multi-family buildings. Low Energy and Sustainable Buildings 2: 1–21.

Ackerman P., Belbo, H., Eliasson, L., de Jong, A, Lazdins, A. & Lyons, J. 2014. The COST model for Calculations of Forest Operations Costs. Int.J.For.Eng. 25(1): 75-81.

Agenzia Nazionale Efficienza Energetica (ENEA). Cos'è la trasmittanza termica. http://www.acs.enea.it/

Bovea M. D., Vidal R. 2004. Materials selection for sustainable product design: A case study of wood based furniture eco-design. Materials and Design 25(2): 111–116.

British Standard Institute (BSI). 2011. PAS 2050: Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. British Standard Institute. London: Institute BS. 2011. p. 37.

Buchanan AH, Honey BG. 1994. Energy and carbon dioxide implications of building construction. Energy and Buildings 20(3): 205–217.

European Organization for Technical Approvals. 2013. European Technical Approval – ETA 13/0799. Österreichisches Institut für Bautechnik, Schenkenstrasse 4, 1010 Vienna, Austria.

European Commission - Joint Research Centre - Institute for Environment and Sustainability.. 2011. ILCD Handbook: Recommendations for Life Cycle Impact Assessment in the European context. Vasa.

European Commission - Joint Research Centre - Institute for Environment and Sustainability. 2010. International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance. Constraints..

FAO. 1992. Cost control in forest harvesting and road construction. 1–106. Can be found at http://www.fao.org/docrep/t0579e/t0579e05.htm

Francescato V, Antonini E , Zuccoli Bergomi L. 2009. Wood Fuels Handbook - Production, quality requirements and trading. Padova, AIEL Italian Agriforestry Energy Association

Frischknecht R, Jungbluth N, Althaus H-J, Doka G, Dones R, Heck T, Hellweg S, Hischier R, Nemecek T, Rebitzer G, Spielmann M. 2004. The ecoinvent Database: Overview and Methodological Framework. The International Journal of Life Cycle Assessment 10(1): 3–9.

Frühwald A. 1996. Ecological aspects of wood-based panels. Paper read at New Challenges for the Wood-Based Panels Industry: Technology, Productivity and Ecology, at Braunschweig.

Goverse T, Hekkert MP, Groenewegen P, Worrell E, Smits REHM. 2001. Wood innovation in the residential construction sector; opportunities and constraints. Resources, Conservation and Recycling 34(1): 53–74.

Gustavsson L, Sathre R. 2006. Variability in energy and carbon dioxide balances of wood and concrete building materials. Building and Environment 41(7): 940–951.

Gustavsson L, Sathre R. 2011. Energy and CO2 analysis of wood substitution in construction. Climatic Change 105(1): 129–153.

Hassan OAB. 2004. Application of value — focused thinking on the environmental selection of wall structures. 70: 181–187.

Hennigar CR, MacLean D., Amos-Binks LJ. 2008. A novel approach to optimize management strategies for carbon stored in both forests and wood products. Forest Ecology and Management 256(4): 786–797.

Hundegger. MHM production line. Online at http://www.hundegger.de.

IPCC 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 1, General Guidance and Reporting. Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). IGES, Japan.

IPCC 2007: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

IPCC 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC 2014a. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland.

IPCC 2014b. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C.Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. Chapter 9: Buildings.

International Standard Organization (ISO). 2006. Environmental management. Life cycle assessment. Principles and framework. ISO 14040. Geneva: International Organization for Standardization.

International Organization for Standardization (ISO). 2006. Environmental management. Life cycle assessment. Requirements and guidelines. ISO 14044. Geneva: International Organization for Standardization.

Kram T, Gielen DJ, Bos AJM, de Feber MAPC., Gerlagh T, Groenendaal BJ, Moll HC, Bouwman ME, Daniëls BW, Worrell E, Hekkert MP, Joosten LAJ, Groenewegen P and Goverse T. 2001. Integrated energy and materials systems engineering for GHG emission mitigation. Final report of the MATTER Project. The Nederlands, 245 p.

Li SH, Xie H. 2013. Building professionals' attitudes towards the use of wood in building design and construction in Taiwan. European Journal of Wood and Wood Products 71(4): 497–505.

Liu G, Han S. 2009. Long-term forest management and timely transfer of carbon into wood products help reduce atmospheric carbon. Ecological Modelling 220(13-14): 1719–1723.

Marcea RL, Lau KK. 1992. Carbon Dioxide Implications of Building Materials. Journal of Forest Engineering 2: 37–43.

MHM – Massive Holz Mauer. Technical data Massiv-Holz-Mauer®. MHM Entwicklungs GmbH. Auf der Geigerhalde 41, D-87459 Prfonten-Weißbach, Deutschland.

Monteiro H, Freire F. 2012. Life-cycle assessment of a house with alternative exterior walls: Comparison of three impact assessment methods. Energy and Buildings. Elsevier B.V. 47: 572–583.

Morel JC, Mesbah a., Oggero M, Walker P. 2001. Building houses with local materials: Means to drastically reduce the environmental impact of construction. Building and Environment 36(10): 1119–1126.

ÖNORM DIN 4074-1:2012. Strength grading of wood – Part 1: Coniferous sawn timber

Ortiz O, Castells F, Sonnemann G. 2009. Sustainability in the construction industry: A review of recent developments based on LCA. Construction and Building Materials. Elsevier Ltd 23(1): 28–39.

Paevere P, MacKenzie C. 2006. Emerging technologies and timber products in construction - compendium. (November): 57.

Pajchrowski G, Noskowiak A, Lewandowska A, Strykowski W. 2014. Wood as a building material in the light of environmental assessment of full life cycle of four buildings. Construction and Building Materials 52: 428–436.

Petersen AK, Solberg B. 2005. Environmental and economic impacts of substitution between wood products and alternative materials: A review of micro-level analyses from Norway and Sweden. Forest Policy and Economics 7(3): 249–259.

Pierobon F, Zanetti M, Grigolato S, Sgarbossa A, Anfodillo T, Cavalli R. 2015. Life cycle environmental impact of firewood production – A case study in Italy. Applied Energy. Elsevier Ltd 150: 185–195.

Pingoud K, Pohjola J, Valsta L. 2010. Assessing the integrated climatic impacts of forestry and wood products. Silva Fennica 44(1): 155–175.

PRé. 2014. Simapro Database Manual. 3–48.

Sartori I, Hestnes a (a?). G. 2007. Energy use in the life cycle of conventional and low-energy buildings: A review article. Energy and Buildings 39(3): 249–257.

Sathre R, Gustavsson L. 2009. Using wood products to mitigate climate change: External costs and structural change. Applied Energy 86(2): 251–257.

Sathre R, O'Connor J. 2010. Meta-analysis of greenhouse gas displacement factors of wood product substitution. Environmental Science and Policy. Elsevier Ltd 13(2): 104–114.

Sathre R, O'Connor J, Connor JO. 2010. A Synthesis of Research on Wood Products & Greenhouse Gas Impacts , 2nd Edition. Vancouver, B.C. FPInnovations. 117 p. (Technical report TR-19R).

Scharai-Rad M. and Welling J. 2002. Environmental and energy balances of wood products and substitutes. Food and Agricultural Organization of the United Nations. Available online at http://www.fao.org/

Schuller O, Hassel F, Kokborg M, Thylmann D, Stoffregen A, Schöll S, Rudolf M. 2013. GaBi Database & Modelling Principles. Pe International (November).

Silvestre JD, Brito J De, Pinheiro MD. 2006. Building ' s external walls in Life-Cycle Assessment (LCA) research studies. 629–638.

Singh A, Berghorn G, Joshi S, Syal M. 2011. Review of Life-Cycle Assessment Applications in Building Construction. Journal of Architectural Engineering, 15–23.

Takano A., Sudip Kumar P., Matti K., Kari A., Mark H. and Stefan W. 2015. The effect of material selection on life cycle energy balance: A case study on a hypothetical building model in Finland. Building and Environment 89 (2015) 192-202.

United Nations Framework Convention on Climate Change (UNFCCC). 2003. Estimation, reporting and accounting of harvested wood products.

Upton B, Miner R, Spinney M, Heath LS. 2008. The greenhouse gas and energy impacts of using wood instead of alternatives in residential construction in the United States. Biomass and Bioenergy 32(1): 1–10.

U.S. Environmental Protection Agency (U.S. EPA). 2006. Life cycle assessment: principles and practice. National Risk Management Research Laboratory, Office of Research and Development, U.S. EPA.

U.S. Environmental Protection Agency (U.S. EPA). 1995. Profile of the nonferrous metal industry. Publication EPA/310-R-95-010, U.S. EPA.

U.S. Environmental Protection Agency (U.S. EPA). 1997. Brick and structural clay production manufacturing. Chapter 11: Mineral Products Industry, Section 11.2. 5th ed. Clearinghouse for Inventories and Emission factors, Technology Transfer Network, U.S. EPA.

Wittstock B, Gantner J, Saunders KLT, Anderson J, Carter C, Gyetvai Z, Kreißig J, Lasvaux ABS, Bosdevigie B, Bazzana M, Schiopu N, Jayr E, Nibel S, Chevalier J, Fullana-i-Palmer JHP, Mundy CGJ-A, Sjostrom TB-WC. 2012. EeBGuide Guidance Document Part B: BUILDINGS . Operational guidance for life cycle assessment studies of the Energy-Efficient Buildings Initiative 1–360.

Ximenes F., Grant T. 2013. Quantifying the greenhouse benefits of the use of wood products in two popular house designs in Sydney, Australia. International Journal of Life Cycle Assessment 18(4): 891–908.

Zabalza Bribián I, Valero Capilla A, Aranda Usón A. 2011. Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. Building and Environment. Elsevier Ltd 46(5): 1133–1140.