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ORIGINAL ARTICLE

Massive wood material for sustainable building design: the Massiv–Holz–Mauer wall system

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Abstract In this study, the emissions to air produced using massive wood material in manufacturing of a Massiv–Holz–Mauer (MHM) wall system have been assessed. The results have been compared with a traditional brick wall. The sustainability of materials was determined using the following impact categories: global warming potential (GWP), ozone depletion potential (ODP), photochemical ozone creation potential (POCP) and human toxicity potential (HTP). Using wood material in building design can reduce the environmental impact to air up to 59 % compared to using traditional material such as brick. The major contributions to the emissions of the MHM wall production are related to the sawmill process, to the manufacturing of fibreboards and aluminium nails. Furthermore, a displacement factor of 0.52 t CO_{2eq} per ton of oven-dried wood for MHM building system used in place of the brick wall was determined for the considered system boundaries.

Keywords Wood · MHM · LCA · Cross-laminated timber

Introduction

The construction industry is an energy-intensive sector rapidly growing in both developed and developing countries [1]. At global level building construction consumes 24 % of the raw materials extracted from the lithosphere [2]. High levels of emissions from the building industry are the result of the energy consumed during the extraction, processing and transportation of materials [3]. According to the Intergovernmental Panel of Climate Change (IPCC) Fifth Assessment Report, in 2010 buildings accounted for 19 % of the energy-related greenhouse gas (GHG) emissions (including electricity) [4]. The demand for energy in the life cycle of buildings is both direct and indirect. Direct energy is used for construction, operation, renovation, and demolition, while indirect energy is consumed by a building for the production of the materials used in its construction and technical installations [5]. To reduce this demand, the use of renewable materials, e.g., wood, represents an effective solution [6–8].

Wood material plays an important role in the modern economy as an alternative to traditional building materials, because of its technological qualities [9]. Wood is, in fact, both light and mechanically resistant, has a good thermal conductivity coefficient, creates a comfortable environment and has good thermal and noise insulation properties. In general, timber-based building systems can be divided into:

- Blockbau systems (or log-haus, blockhaus, etc.), structural systems representing a technology of ancient origins, but used in modern practice for the construction of residential and commercial buildings, generally up to two levels. These structures are commonly obtained by assembling multiple timber logs stacked horizontally one upon each other [10];

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- Timber frame systems (or shear walls) which are, in most of Europe, usually prefabricated elements. They consist of a timber frame, with hinged connections, sheathed by wood-based panels connected to the frame by metal fasteners [11];
- Cross-laminated timber (CLT) systems (called also "X-Lam," "Massive Timber" or "Cross-Lam"). In these systems, boards are glued side by side in a single layer and then glued to another layer of boards placed at right angles with the adjacent layers [12]. The cross-lamination design improves rigidity, stability, and mechanical properties. Compared to the other systems, the CLT presents several advantages: speed and efficiency of installation, thanks to the prefabrication; design flexibility; cost competitiveness; fire protection; seismic performance; thermal performance and energy efficiency; resource efficiency—it can use smaller-dimension material that might not otherwise be used in structural applications [13]. Furthermore, CLT structures could prove to be a viable alternative to concrete and steel for mid- to high-rise buildings [14].

Within the CLT systems group, a new building system, called Massiv–Holz–Mauer (MHM), has been patented in Germany in 2005. In MHM building system, the crossed layers of boards are jointed by aluminium screws and no adhesives are used. The specifications of MHM walls can be found in the European Technical Approval (ETA) for MHM [15]. Its production line, nearly entirely automatic, is described on the Hundegger website [16].

Wood is commonly regarded as the most environmentally friendly material in building design and construction [17]. Several studies have demonstrated that the use of wood for building in substitution to other materials causes less GHG emissions [2, 18–22]. A review and synthesis of various international studies on wood products concludes that manufacturing wood products requires less total energy, and in particular less fossil energy, than manufacturing 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 [23]. Furthermore, recent studies also indicate that wood-based wall systems entail 10–20 % less embodied energy than traditional concrete systems [24, 25].

The lower environmental impacts of wood products compared to other materials are also related to the fact 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 (carbon neutrality assumption) [26, 27]. Moreover, long-lasting wood products, e.g., wood products for buildings, have an additional benefit on climate change, since during their entire lifetime they act like temporary CO_2 storages, storing carbon in their biomass that would have otherwise been emitted to the atmosphere [2, 28]. Lastly, using wood products at their end of life as a substitute energy source, the emissions from other sources, such as fossil fuels, could be reduced [29]. When comparing the overall environmental impacts of wood products with traditional materials, 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 [30].

In literature several studies have been carried out on CLT environmental performances [31–35]; however, the authors are not aware of any previous research carried out on the environmental impacts of the MHM system, besides a compendium of wood products and technologies in construction funded by the Australian government which emphasized the absence of glue in this building system [36]. Since MHM represents an innovative and recent building system (its licence was submitted in 2012) its environmental advantages have not been yet studied. 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 [37]. In this framework, the objective of this study is to perform a comparative cradle-to-gate life cycle assessment (LCA) in order to evaluate the environmental impacts in terms of emissions to air produced from materials used in the construction of an MHM wall system and a brick wall one.

Materials and methods

In Italy, the most requested MHM wall system for the construction of individual dwelling houses is 28.5 cm thick. From the inside to the outside, the wall system consists of the following materials: plasterboard, 9 Norway spruce (*Picea abies* L.) layers of boards connected by aluminium nails, transpiring geotextile, insulating fibreboards (2 × 40 cm), mortar, plaster mesh, and plaster for outer covering (corresponding, respectively, to letters a–g in Fig. 1a). The Norway spruce boards have a water content of 13 %, a density of 480 kg m^{-3} and a thickness of 23 mm. The thermal transmittance (*U* value) of the 28.5-cm-thick MHM wall system is 0.21 W m^{-2} K^{-1}.

For the comparison, an exterior brick wall able to ensure the same thermal transmittance characteristics has been used. The brick wall used for comparison is 40 cm thick, which is a widely used wall system in Italy for the construction of individual dwelling houses [39]. Its elements

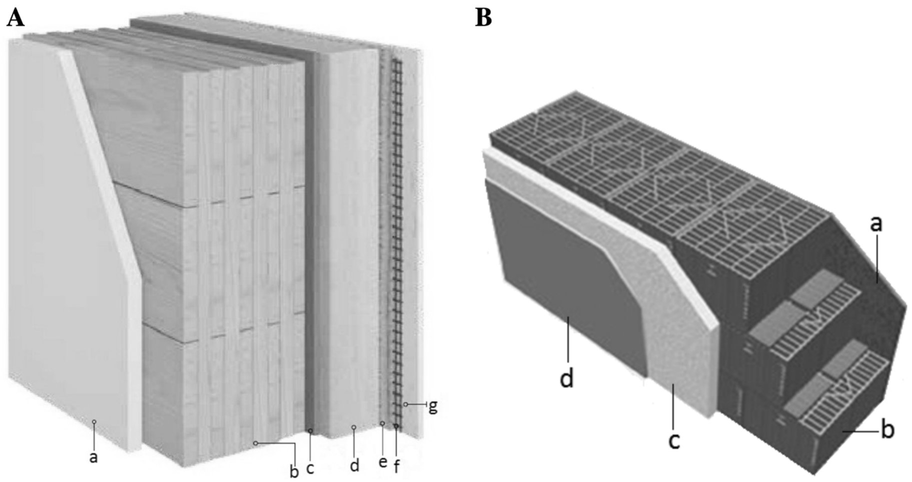

Fig. 1 **A** Massiv–Holz–Mauer (MHM) wall system (*a* plasterboard, *b* 9-layer spruce boards, *c* geotextile, *d* fibreboards, *e* mortar, *f* plaster mesh, *g* plaster) [38]; **B** brick wall system (*a* lime and cement plaster layer; *b* perforated clay bricks + mortar on the horizontal surfaces of the bricks, *c* insulating panel in extruded polystyrene foam (XPS), *d* lime and cement mortar layer

are: plaster, perforated clay bricks with mortar on their horizontal surfaces, insulating panel of extruded polystyrene foam (XPS), and mortar for outer covering (Fig. 1b). The weight of 1 m^2 of MHM system is 128 kg while the weight of 1 m^2 brick wall is 313 kg.

Data collection included both primary and secondary data. Tables 1 and 2 detail the inputs and outputs of MHM and brick LCA models. In the MHM wall, the Norway spruce wood density at 50 % of moisture content is assumed to be 750 kg m^{-3} until the boards air drying process. After air drying the moisture content decreases to 12 % and the density changes to 480 kg m^{-3}. The trees are motor manual felled by a chainsaw (tree felling) and then hauled as full tree for a short distance (50 m) by tractor equipped with a winch (extraction). Chainsaw is the most used equipment in North Eastern Italy for tree felling. The wood harvesting produces 30 % of residues which are left to decompose in forest. Forest operations are then performed by means of a chainsaw to transform full tree in logs (landing) which are transported with a 32-t payload EURO5 truck to the sawmill.

Primary data on quantities of materials and energy needed to produce and transport wooden boards to build 1 m^2 of MHM wall have been collected in 2015. Information has been provided by a sawmill and by a construction company. The selected companies, in terms of use of material, production processes and energy mix utilized, are representative of the sectorial Italian small and medium enterprises. Data about energy and fuel used to make MHM boards were calculated as a percentage on the total consumptions of the sawmill. This percentage was considered equivalent to the percentage of MHM boards processed in 1 year (400 m^3) on the total production of the sawmill. This resulted in 0.6 L of diesel and 13 kWh of electricity (31 % from renewable sources) for 1 m^2 × 9 layers of wood necessary to build 1 m^2 of MHM. On the other hand assembling energy at the company is 10 kWh for 1 m^2 of wall. The planks are transported by truck for 186 km from the sawmill to the MHM producing company where the timber walls are assembled; other transportation means are not suitable for this short distance.

Secondary data were used for the production processes of the other materials necessary to build an MHM wall and for all the components, processes and transports of the brick wall (Tables 1, 2). These data were provided by the Ecoinvent database [40].

LCA was used to assess the environmental impact of the studied materials. LCA is a standardized and worldwide recognized methodology. This technique enables the environmental performance of materials to be evaluated during their entire life cycle [37, 41, 42].

GaBi 6 software was used to perform the analysis, to generate the emission factors and to analyze the relative contribution of the processes to the total emissions. GaBi 6 is a software package developed by PE International designed for analyzing the environmental impact of products and services [43].

The functional unit is for both systems 1 m^2 of exterior wall, ensuring a thermal transmittance of 0.21 W m^{-2} K^{-1}. The investigated system boundaries for both systems are defined to be cradle-to-gate. They include life cycle stages from the extraction or acquisition of raw materials to the point at which the product leaves the organization undertaking the assessment [44].

The system boundaries for MHM and for brick wall building systems are illustrated, respectively, in Figs. 2 and 3. Specific information about energy and fuel flows is reported in Tables 1 and 2. For both the systems four impact categories were determined using the impact assessment method of the Institute of Environmental Science of Leiden University (CML) 2001—Apr. 2013 methodology: global warming potential (GWP), OZONE DEPLETION POTENTIAL (ODP), photochemical ozone creation potential (POCP) and human toxicity potential

Table 1 Flows (inputs and outputs) of 1 m^2 Massiv–Holz–Mauer (MHM) wall manufacturing processes

Wooden boards	Input	Output
Tree feeling	Spruce tree in forest (0.386 m^3) Energy (diesel) consumed by a 3.6-kW chainsaw to manual felling the tree (time: 0.035 h)	Felled spruce tree (0.297 m^3) without branches [Tree waste (0.062 m^3) not taken into account in the LCA[a] model]
Extraction	Felled spruce tree (0.297 m^3) Energy (diesel) consumed by a 4 wheel drive 67-kW tractor equipped with a winch to extract the felled tree—distance 50 m	Felled spruce tree (0.297 m^3)
Landing	Felled spruce tree (0.297 m^3) Energy (diesel) consumed by a 3.6-kW chainsaw to manually cut the tree ($h = 0.035$ h)	Logs (0.297 m^3)
Road transport to sawmill	Logs (0.297 m^3) Energy (diesel) consumed by a 32-t payload EURO5 truck to transport the logs per 133 km	Logs (0.297 m^3—50 % moisture content)
Log handling at sawmill	Logs (0.297 m^3) Energy (diesel): 0.27 kg Lubricant: 0.0061 kg	Logs (0.297 m^3—50 % moisture content)
Log processing at sawmill	Logs (0.297 m^3) Energy (diesel): 0.0073 kg Energy (electricity mix): 47.07 MJ Lubricant: 4.00E−07 kg	Boards (0.297 m^3) [Saw dust (0.025 m^3) + wood chips (0.065 m^3) not taken into account in the LCA model]
Boards air drying	Boards (0.297 m^3 at 50 % moisture content)	Boards (0.207 m^3 at 12 % moisture content)
Boards handling with machine	Boards (0.207 m^3) Energy (diesel): 0.46 kg Lubricant: 0.108 kg	Boards (0.207 m^3)
Boards transport to the company	Boards (0.207 m^3) Energy (diesel) consumed by a 32-t payload EURO5 truck to transport the boards per 166 km	Boards (0.207 m^3)
Aluminium nails	RER[b]: metal working, average for aluminium product manufacturing Energy (diesel) consumed by a 32-t payload EURO5 truck to transport the aluminium nails per 600 km	Aluminium nails (0.7 kg)
Plasterboard	CH[c]: gypsum plasterboard production Energy (diesel) consumed by a 16–32 t payload EURO5 truck to transport the plasterboard per 200 km	Plasterboard (9.5 kg)
Geotextile	RER: fleece production, polyethylene Energy (diesel) consumed by a 16–32 t payload EURO5 truck to transport the geotextile per 150 km	Geotextile (0.15 kg)
Fibreboard	CH: fibreboard production, soft, from wet processes Energy (diesel) consumed by a 32-t payload EURO5 truck to transport the geotextile per 600 km	Fibreboard (0.08 m^3)
Mortar	RoW[d]: cement mortar production Energy (diesel) consumed by a 32-t payload EURO5 truck to transport the mortar per 200 km	Mortar (6 kg)
Plaster mesh	RER: glass fiber production Energy (diesel) consumed by a 32-t payload EURO5 truck to transport the plaster mesh per 200 km	Plaster mesh (0.15 kg)
Plaster	CH: cover plaster production, mineral Energy (diesel) consumed by a 32-t payload EURO5 truck to transport the plaster per 200 km	Plaster (2.5 kg)

Table 1 continued

Wooden boards	Input	Output
MHM assembling	IT[e]: energy production photovoltaic, 3KWp slanted-roof installation, single-Si, panel, mounted—10.8 MJ IT: electricity, high voltage, production mix—25.2 MJ	1 m^2 of MHM wall

[a] Life cycle assessment

[b] Europe

[c] Switzerland

[d] Rest of the world

[e] Italy

(HTP). The time frame for the assessment of the global warming impact was 100 years, as recommended by the Publicly Available Specification (PAS) 2050 [44].

Lastly, a displacement factor was calculated to quantify the amount of emission reduction achieved per unit of wood material use [30], expressed in terms of t CO_{2eq} emission reduction per t of oven-dry wood product.

Results

Environmental assessment of materials used to produce 1 m^2 of MHM wall

The results of the LCA model for the MHM wall production processes are summarized in Table 3.

In terms of GWP, the production of 1 m^2 of MHM emits 35.23 kg CO_{2eq}. The main processes which contribute to it are: the sawmill process (31 %), the fibreboards manufacturing (22 %) and the electricity production for the final assembling of the wall (14 %). The energy-related emissions are almost totally due to the non-renewable electricity production. The sawmill process produces 10.74 kg CO_{2eq}. The log processing is responsible for 82 % of the emissions: this amount is again caused by the electricity production mix.

Concerning the ODP, producing 1 m^2 of MHM generates 4.37 mg $R11_{eq}$. The main processes influencing the ODP emissions are the sawmill process, the fibreboard phase and the energy production for MHM assembling.

At local scale, POCP results in 32.19 g $ethene_{eq}$ and it is mainly caused by the forest operations (57 %) mainly due to the use of chainsaw for tree felling and landing operations. Sawmill and fibreboard processes also affect this impact category, producing 14 and 10 % of POCP gases, respectively.

As POCP, HTP (9.71 kg DCB_{eq}) shows a slightly more uniform distribution of emissions between electricity (8 %), plaster mesh and fibreboards manufacturing (15 %) and sawmill processes (17 %), but aluminium manufacturing is the main pollutant process in terms of HTP (30 %).

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; the producer could improve its photovoltaic panels system for this purpose. If the totality of the 10 kWh needed to assemble 1 m^2 of wall was from photovoltaic source, the GWP emissions related to electricity would decrease by 84 % and the overall GWP emissions for MHM would decrease by 2 %.

Except for forest operations, where the transport phase accounts for 85 % of GWP, it is remarkable that for all impact categories and for all materials needed to build 1 m^2 of MHM it is the production process, and not the transport, that accounts for the largest percentage of emissions, even though the transport distances are sometimes considerable (e.g., 600 km for aluminium nails and fibreboards). This is due to the light weight of these materials (e.g., 0.7 kg aluminium nails and 10.8 kg fibreboards per functional unit). The wooden boards transport contributes to GWP with 13 % emissions of CO_{2eq} on the total CO_{2eq} attributed to the whole sawmill process. The other materials transport-related emissions vary between 0.7 % (plaster mesh) and 11 % (plaster) CO_{2eq} of the total emissions relative to the production of each material. The higher value for the wooden boards is due to the greater quantity of wood needed for 1 m^2 of MHM. In any case the emissions related to transport would increase if the sawn wood was bought further away, meaning that the local production chain should be encouraged in order to keep the transport environmental impact as low as possible.

Table 2 Flows (inputs and outputs) of 1 m^2 brick wall manufacturing processes

	Input	Output
Brick	RER[a]: brick production	Bricks (227 kg)
	Energy (diesel) consumed by a 32-t payload EURO5 truck to transport the bricks per 84.2 km	
Plaster	RER: cover plaster production, mineral	Plaster (27 kg)
	Energy (diesel) consumed by a 32-t payload EURO5 truck to transport the plaster per 200 km	
Light mortar	CH[b]: light mortar production	Light mortar (1 kg)
	Energy (diesel) consumed by a 32-t payload EURO5 truck to transport the light mortar per 342 km	
Polystyrene XPS panels	CH: polystyrene foam slab for perimeter insulation	Polystyrene XPS[c] panels (2.4 kg)
	Energy (diesel) consumed by a 32-t payload EURO5 truck to transport the polystyrene XPS panel per 264 km	
Mortar	CH: cement mortar production	Mortar (5.4 kg)
	Energy (diesel) consumed by a 32-t payload EURO5 truck to transport the mortar per 200 km	
Brick wall assembling (manually)	Bricks + plaster + light mortar + polystyrene XPS panels + mortar	1 m^2 of brick wall

[a] Europe

[b] Switzerland

[c] Extruded polystyrene foam

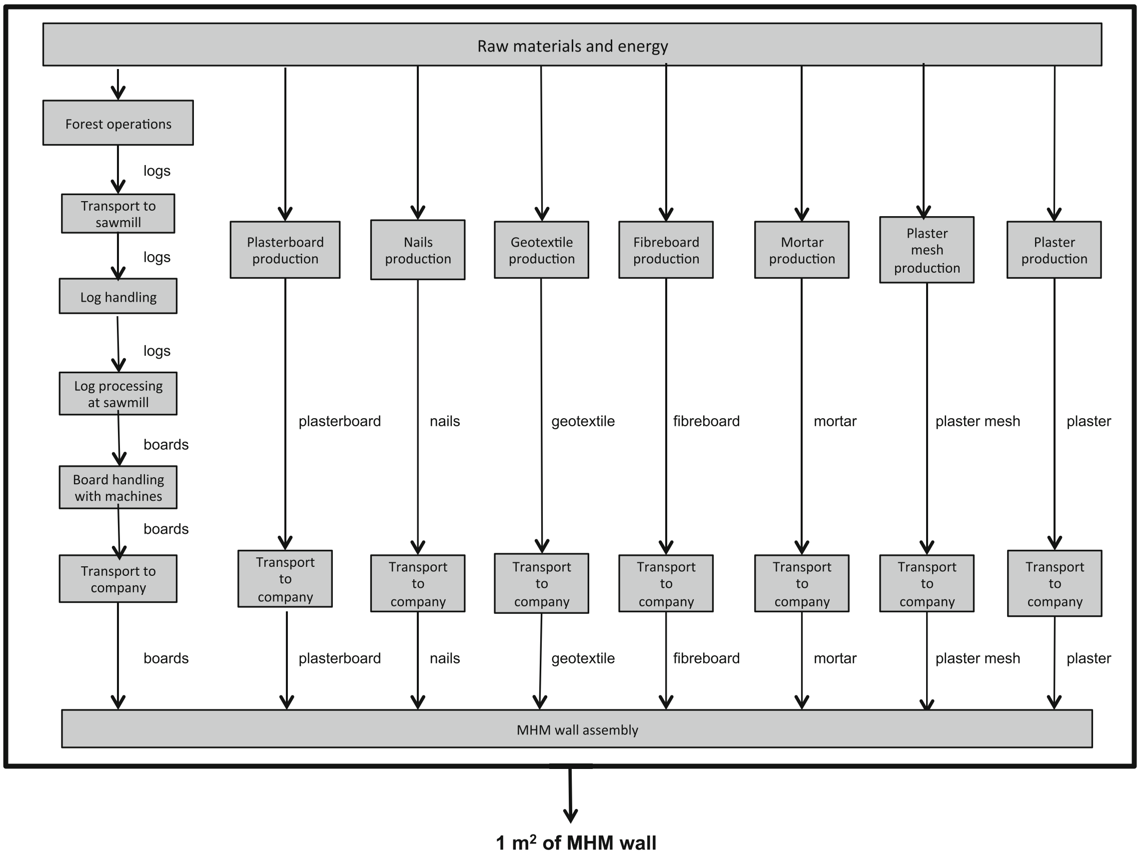

Fig. 2 Cradle-to-gate system boundaries for Massiv–Holz–Mauer (MHM) wall system

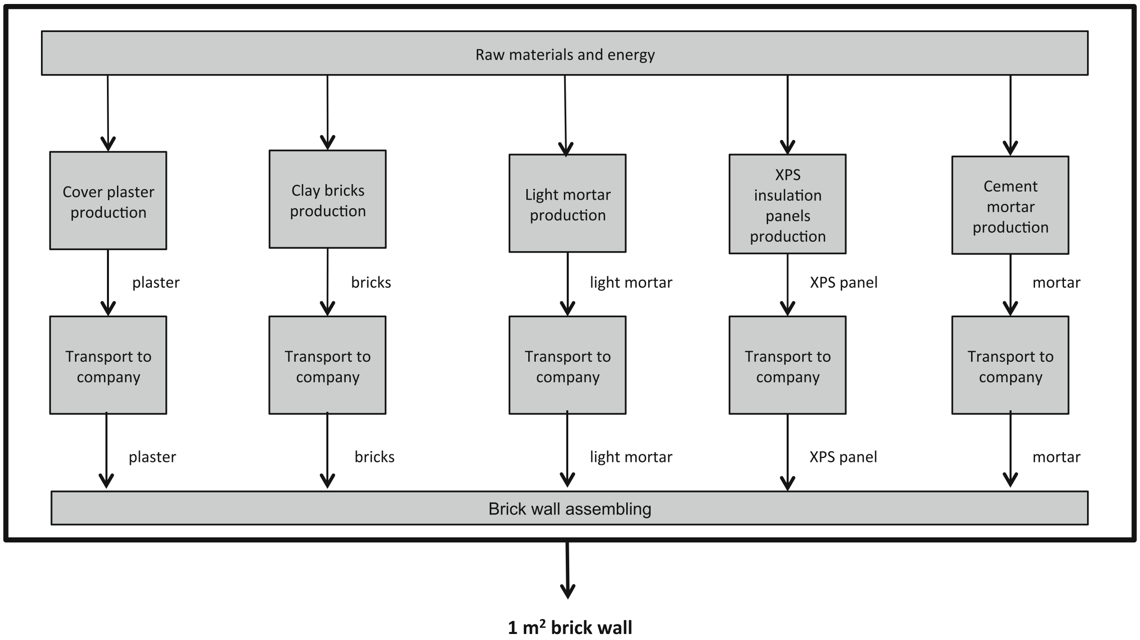

Fig. 3 Cradle-to-gate system boundaries for brick wall system

Comparison between MHM and brick wall

Figure 4 shows the comparison of the overall impact of the two production processes. The wooden building system shows a better environmental performance for all the analyzed impact categories. Table 4 shows the contribution of brick wall materials production processes to the four impact categories considered in this study. The GWP of the brick wall (85.90 kg CO_{2eq}) is more than double than the GWP of MHM (35.23 kg CO_{2eq}). As wrote before, the POCP value of forest operations is affected by the emissions of chainsaw but the MHM still performs better than brick with 9.45 g ethene_{eq} less. ODP and HTP of MHM are, respectively, 40 and 50 % lower than brick wall. In fact, the brick wall provides 7.32 mg $R11_{eq}$ against 4.38 mg $R11_{eq}$ and 19.46 kg DCB_{eq} (1,4-dichlorobenzene) instead of 9.71 kg DCB_{eq} of MHM.

To better understand the contributions to the four impact categories of the production of 1 m^2 of MHM and brick wall, Table 5 shows the list and values of the emitted chemicals. 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). Note that in Ecoinvent long-term emissions are defined as emissions occurring more than 100 years after present.

Carbon dioxide is the main contributor to GWP, with 27.61 kg CO_2 for MHM and 78.93 kg CO_2 for the brick wall. The main sources of non-biotic carbon are fossil fuel combustion in industrial processes and in electricity production. Compared to fossil carbon, biogenic carbon is emitted in minor quantity. Biogenic carbon dioxide emitted from brick wall production is lower (1.85 kg CO_2) than that of MHM wall since no wood biomass is involved in its production, while MHM biogenic CO_2 (4.95 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. Based on international standards and guidelines, the biogenic carbon dioxide is not accounted in LCA studies (carbon neutrality assumption) or is reported separately [45]. In this work the second option has been chosen. Methane has a GWP of 28 for a time horizon of 100 years [46] and is indeed the third highest greenhouse gas that is produced from both MHM (1.99 kg) and brick wall building systems (4.64 kg). 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 manufacturing. 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.

As mentioned above, the ODP for the MHM production process corresponds to 60 % of the ODP for the brick wall (Fig. 4). Halogenated organic emissions are 4.37 mg $R11_{eq}$ for the former and 7.32 mg $R11_{eq}$ for the latter. Halon is the emission which mostly contributes to the total halogenated gases in both cases; it is particularly high for brick

Table 3 Contributions of Massiv–Holz–Mauer (MHM) wall materials production process to global warming potential (GWP), ozone depletion potential (ODP), photochemical ozone creation potential (POCP), human toxicity potential (HTP) for the production of 1 m^2 of wall

Specific contributions	GWP (kg CO_{2eq})	ODP (mg $R11_{eq}$)	POCP (g $Ethene_{eq}$)	HTP (kg DCB_{eq})[a]
Total	35.231	4.373	32.185	9.714
Plasterboard	3.062	0.267	1.218	0.714
Manufacturing	2.737	0.208	1.047	0.568
Transport	0.325	0.059	0.171	0.147
Forest operations	2.600	0.437	18.174	0.463
Tree felling	0.193	0.037	8.365	0.054
Extraction	0.002	0.000	0.002	0.003
Landing	0.193	0.037	8.365	0.054
Road transport	2.211	0.363	1.442	0.351
Sawmill process	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
Transport	1.426	0.267	0.927	0.519
Aluminium nails	3.168	0.157	1.906	2.944
Manufacturing	3.133	0.150	1.883	2.931
Transport	0.036	0.007	0.023	0.013
Geotextile	0.412	0.008	0.439	0.056
Manufacturing	0.408	0.008	0.437	0.054
Transport	0.004	0.001	0.002	0.002
Fibreboard	7.560	0.890	3.189	1.429
Manufacturing	6.988	0.783	2.817	1.221
Transport	0.572	0.107	0.372	0.208
Mortar	1.958	0.089	0.530	0.244
Manufacturing	1.855	0.069	0.464	0.207
Transport	0.102	0.019	0.066	0.037
Plaster mesh	0.372	0.033	0.191	1.364
Manufacturing	0.370	0.032	0.189	1.363
Transport	0.003	0.001	0.002	0.001
Plaster	0.389	0.036	0.187	0.089
Manufacturing	0.347	0.028	0.159	0.074
Transport	0.043	0.008	0.028	0.015
Assembling (electricity)	4.973	0.602	1.762	0.806
Photovoltaic	0.232	0.033	0.179	0.276
Non-renewable	4.740	0.569	1.583	0.530

[a] 1,4-dichlorobenzene

production (3.56 mg $R11_{eq}$ of Halon 1211 and 2.87 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, but they have a high ozone depletion potential.

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 21.61 g $ethene_{eq}$ of MHM are mainly caused by the chainsaw used (14.14 g $ethene_{eq}$). On the other hand, it is again the brick production process which contributes the most to 17.63 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 lower than those relative to the brick wall (Table 5). Sulphur oxides and unspecified hydrocarbons emissions are similarly low.

Lastly, the HTP produced from brick wall manufacturing process is twice (19.46 kg DCB_{eq}) the HTP of the MHM production (9.71 kg DCB_{eq}). Heavy metals, such as chromium (+VI), arsenic, nickel, cadmium and copper, contribute heavily to HTP impact category both for MHM and for the brick wall. Emissions of heavy metals to air are

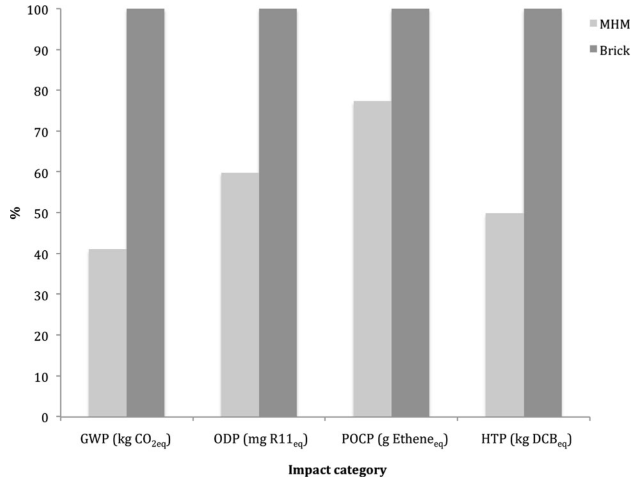

Fig. 4 Massiv–Holz–Mauer (MHM) and brick wall production processes comparison in terms of relative environmental impacts for the impact categories global warming potential (GWP), ozone depletion potential (ODP), photochemical ozone creation potential (POCP), human toxicity potential (HTP)

related to secondary aluminium industry [47] as well as to brick manufacturing [48] and are, in descending 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 >PM10). This impact category includes dust particles and silicon dust, with 0.08 kg DCB_{eq} for the brick wall and 0.15 kg DCB_{eq} for MHM, where emitted particles are mainly PM >10 caused by aluminium manufacturing (0.12 kg DCB_{eq}).

Displacement factor

1 m^2 of MHM wall contains 98.4 kg of wood at 13 % of water content (density of 480 kg/m^3). This corresponds to 97.1 kg (0.0971 t) of oven-dry wood. Considering that GHG emissions of 1 m^2 of MHM wall are 35.23 kg CO_{2eq} (0.0326 t CO_{2eq}), while the GHG emissions for 1 m^2 of brick wall are 85.90 kg CO_{2eq} (0.0859 t CO_{2eq}), the solved equation [30] for the displacement factor (DF) is:

$$\begin{aligned}\mathrm{DF} &= \frac{\text{GHG brick} - \text{GHG MHM}}{\text{Wood mass MHM} - \text{Wood mass brick}} \\ &= \frac{0.0859\ \mathrm{t\ CO_{2eq}} - 0.0325\ \mathrm{t\ CO_{2eq}}}{0.0971\ \mathrm{t} - 0} \\ &= 0.52\ \mathrm{t\ CO_{2eq}/t}\end{aligned}$$

This means that for each t of wood used to build a wall in MHM instead of bricks, 0.52 t CO_{2eq} of emissions are avoided. This value is low if compared to a previous study [30] in which a meta-analysis of greenhouse gas displacement factors of wood product substitution was performed. The authors found an average value of 3.9 t CO_{2eq} emission reduction. Yet the authors assert that the displacement factors vary widely between the 21 analyzed 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: MHM producer), equal to 18.95 t of oven-dry matter. As a consequence,

Table 4 Contributions of brick wall materials production process to global warming potential (GWP), ozone depletion potential (ODP), photochemical ozone creation potential (POCP), human toxicity potential (HTP) for the production of 1 m^2 of wall

Specific contributions	GWP (kg CO_{2eq})	ODP (mg $R11_{eq}$)	POCP (g $Ethene_{eq}$)	HTP (kg DCB_{eq})[a]
Total	85.904	7.318	41.628	19.461
Brick	69.997	6.485	30.902	17.178
Manufacturing	68.371	6.181	29.845	16.586
Transport	1.626	0.304	1.057	0.592
Plaster	4.206	0.392	2.017	0.963
Manufacturing	3.747	0.306	1.718	0.796
Transport	0.459	0.086	0.299	0.167
Light mortar	0.592	0.027	0.174	0.098
Manufacturing	0.563	0.022	0.155	0.087
Transport	0.029	0.005	0.019	0.010
Polystyrene XPS[b] panels	9.741	0.334	8.173	1.036
Manufacturing	9.687	0.324	8.138	1.016
Transport	0.054	0.010	0.035	0.020
Mortar	1.368	0.080	0.362	0.187
Manufacturing	1.276	0.062	0.302	0.154
Transport	0.092	0.018	0.060	0.033
Assembling (manually)	0.000	0.000	0.000	0.000

Brick wall (1 m^2)

[a] 1,4-dichlorobenzene

[b] Extruded polystyrene foam

Table 5 Contributions to emissions of chemicals for the production of 1 m^2 of Massiv–Holz–Mauer (MHM) and brick wall. The values are referred to the emissions after characterization ("Characterization" column) and before characterization ("Inventory" column)

Classification	MHM wall		Brick wall	
Global warming potential (GWP)	Characterization kg CO_{2eq}	Inventory kg	Characterization kg CO_{2eq}	Inventory kg
Emissions to air (total)	35.23	32.65	85.90	80.98
Carbon dioxide	27.61	27.61	78.93	78.93
Carbon dioxide (biotic)	4.95	4.95	1.85	1.85
Nitrous oxide (laughing gas)	0.37	1.24E−03	0.23	7.82E−04
Sulphur hexafluoride	0.03	1.64E−06	0.05	2.09E−06
Methane	1.99	0.08	4.64	0.19
Methane (biotic)	0.19	0.01	0.18	0.01
Halogenated organic emissions[a]	0.08	1.74E−05	0.02	7.92E−06
Ozone depletion potential (ODP)	mg $R11_{eq}$	mg	mg $R11_{eq}$	mg
Emissions to air (total)	4.38	2.66	7.32	6.95
Halogenated organic emissions	4.37	2.66	7.32	6.95
Long term to air (ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113)	1.17E−03	1.17E−03	1.85E−04	1.85E−04
Photochemical ozone creation potential (POCP)	g $Ethene_{eq}$	g	g $Ethene_{eq}$	g
Emissions to air (total)	32.18	5376.77	41.63	718.34
Group NMVOC[b] to air	21.61	60.24	25.39	69.82
Sulphur dioxide	4.08	85.07	5.96	124.11
Nitrogen oxides	1.97	70.62	4.56	162.89
Carbon monoxide	3.61	133.92	4.46	165.17
Carbon monoxide (biotic)	0.38	4939.56	0.10	3.77
Methane	0.47	79.74	1.11	185.40
Methane (biotic)	0.05	7.63	0.04	7.23
Human toxicity potential (HTP)	kg DCB[j]$_{eq}$	kg	kg DCB_{eq}	kg
Emissions to air (total)	9.71	0.41	19.46	0.46
Heavy metals to air[c]	5.01	2.39E−04	6.40	3.52E−04
Organic emissions to air (group VOC)[d] (mainly PAH[e], halogenated organic emissions, other NMVOCs[f])	2.46	0.06	3.36	0.06
Inorganic emissions to air[g]	1.68	0.16	9.17	0.30
Long term to air[h]	0.42	3.99E−04	0.45	4.32E−04
Particles to air (mainly >PM[i]10, PM2.5—PM10, PM2.5)	0.15	0.19	0.08	0.10

[a] Tetrafluoromethane, R 116 (hexafluoroethane), R 114 (dichlorotetrafluoroethane), R 22 (chlorodifluoromethane), Halon (1301), perfluoropentane, Halon (1211), R 113 (trichlorotrifluoroethane), R 134a (tetrafluoroethane), R 152a (difluoroethane), R 23 (trifluoromethane), R 12 (dichlorodifluoromethane), carbon tetrachloride (tetrachloromethane), R 124 (chlorotetrafluoroethane), chloromethane (methyl chloride), dichloromethane (methylene chloride), 1,1,1-trichloroethane, R 11 (trichlorofluoromethane), methyl bromide

[b] Non-methane volatile organic compounds

[c] Arsenic, chromium (+VI), nickel, antimony, cadmium, vanadium, copper, selenium, molybdenum, cobalt, thallium, chromium (unspecified), lead, mercury, zinc, tin, hydrogen arsenic (arsine)

[d] Volatile organic compounds

[e] Polycyclic aromative hydrocarbon

[f] Benzene, NMVOC (unspecified), ethylene oxide, propylene oxide, acrolein, formaldehyde (methanal), ethene (ethylene), toluene (methyl benzene), ethyl benzene, xylene (dimethyl benzene), phenol (hydroxy benzene), butadiene, xylene (meta-xylene; 1,3-dimethylbenzene), xylene (ortho-Xylene; 1,2-dimethylbenzene), Styrene

[g] Hydrogen fluoride, nitrogen oxides, barium, sulphur dioxide, beryllium, hydrogen chloride, ammonia, carbon disulphide, hydrogen sulfide, sulphur oxides

[h] Chromium VI, arsenic, nickel, vanadium, copper, beryllium, selenium, cadmium, cobalt, molybdenum, barium, lead, particulates >10 µm, particulates >2.5 and <10 µm, particulates <2.5 µm, zinc, antimony, mercury, hydrogen sulfide, tin

[i] Particulate matter

[j] 1,4-dichlorobenzene

considering the system boundaries used in this study, the emissions avoided for 100 m^2 of MHM house when compared to a brick house of the equal dimension, are:

$$18.95\ \text{t} \times 0.52\ \text{t}\ \text{CO}_{2\text{eq}}/\text{t} = 9.85\ \text{t}\ \text{CO}_{2\text{eq}}$$

Discussion

These results are consistent with other studies comparing wood and different building materials which found wood to be among the most environmentally sustainable building material. It is remarkable though that most studies on this topic compare steel or concrete instead of brick to wooden walls or houses. Among the studies which compare timber and bricks, both Goverse et al. [21] and Monteiro and Freire [49] found a possible reduction in CO_2 of almost 50 % when using wood. In an application of value-focused thinking, Hassan [50] investigated three exterior wall types: masonry, concrete and timber. The functional unit the author chose for the LCA is 1 m^2 of wall with U value 0.2 W m^{-2} K^{-1}. Although the brick and timber wall designs are different from those here analyzed, the wooden wall was proven to be the best option from an 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. [51] determined in 2001 emissions of 18 t CO_2 for the wood version and 27 t CO_2 for the brick version. In this case, the wooden house emissions were one-third lower than those attributed to the brick house. However, specifications about the boundaries and sections of the walls were not given. On the other hand, Marcea and Lau [52] calculated the energy and CO_2 cost of similarly performing residential buildings, finding that the brick assembly emitted 1.9 times more than the wooden assembly.

In this research the results show that the wooden wall emits nearly 60 % less CO_{2eq} than the brick wall. As a consequence, the wood construction is confirmed to have a lower impact on global warming than the brick alternative, even if 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. Moreover, in terms of GWP, compared to the brick wall, the wooden wall has the additional benefit of acting as a carbon storage for all its lifetime. To better understand the contribution of carbon storage, a comprehensive carbon balance should be performed, including carbon sequestration in forest and biogenic emissions after the lifetime of the wood product. This would require a cradle-to-grave approach, which is outside the system boundaries of this study. Another aspect that should not be neglected when comparing the two systems is the weight of wood construction. The substitution of the traditional building materials with wood leads to large reductions in the weight of houses, which could substantially contribute to the dematerialization in the construction sector [20]. The difference of weight is high also between MHM wall and brick wall, with the former being about 60 % lighter than the latter.

Conclusions

In this study an LCA was performed to assess the emissions to air caused by the production of materials used in a Massiv–Holz–Mauer (MHM) wooden wall and a brick wall. The results were compared to determine which of the two systems had the lowest environmental impacts.

For all the four impact categories considered, Global Warming Potential, Photochemical Ozone Creation Potential, Ozone Depletion Potential and Human Toxicity Potential, the MHM wall construction showed lower emissions to air compared to the brick wall. GWP and POCP represented, respectively, 40 and 77 % of the traditional wall emissions, while ODP and HTP were, respectively, 60 %, and 50 % of the emissions related to the brick wall building materials production. MHM was proven to be an extraordinary building material, which, while ensuring the same technical performance of bricks, is much more environmentally sustainable in terms of both global and local impact.

To further reduce the environmental impact of MHM, the main areas of improvement can be identified in the log processing, fibreboards manufacturing, and aluminium nails manufacturing for GWP and POCP. The energy production for the final assembling of the wall also caused a remarkable share of emissions. ODP was influenced by the emissions from the sawmill and from fibreboard and electricity production. Interventions on the aluminium nails production would also be critical in the reduction of the impact on HTP.

Overall, the use of MHM can represent a great opportunity to reduce the emissions in the construction industry. It was calculated that if bricks were replaced by MHM, for each oven dry t of wood used to build a wall in MHM instead of bricks, 0.52 t CO_{2eq} of emissions, equal to the displacement factor, would be avoided.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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