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Comparing the environmental impacts of wooden buildings in Spain, Slovenia, and Germany

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ABSTRACT

The environmental impacts of a wooden single-family model house were compared in different locations in Europe using Life Cycle Assessment. The chosen locations were Munich, Ljubljana, Portorož, Madrid, and Valencia. The main purpose was to analyze the existing barriers for designing a regenerative wood house and how those barriers change depending on the local conditions. The LCA results show that, despite the highly insulative building envelope, the use phase still contributes between 65% and 76% of the total carbon emissions over the complete life cycle of the house. Carbon emissions and the overall environmental impacts are higher in the locations with a colder climate, due to the energy used for heating. However, the electricity generation mix can sometimes overshadow those differences. Due to that influence, the carbon emissions in Munich are much higher than in Ljubljana despite having a similar energy consumption. The electricity mix effect is also observed when comparing the environmental impacts in Madrid and Portorož, where the CO_2 emissions are slightly higher in Madrid despite its lower energy consumption. These results demonstrate the need for taking measures to overcome the impacts that are not possible to elimin–ate by passively isolating the house.

1. Introduction

As the third decade of the 21st century begins, climate change is a more pressing threat than ever. Since the first climate emergency declaration in 2016 (Ripple et al., 2020), 25 countries and more than 1250 local governments have made climate emergency declarations. The effects of climate change are becoming more apparent in several areas of the world and are causing severe damage in the most impoverished ones (Climate Centre, 2018). Clearly, current sustainability efforts are not enough. To bring ecosystems back to healthy states, a regenerative approach that includes aggressive steps to achieve environmental restoration along with behavioral change is necessary. The target should be to achieve regenerative sustainability, allowing both society and the environment to maintain a healthy balance and to evolve (COST Action RESTORE, 2018).

Therefore, it is essential to analyze and optimize every industry sector, including the construction sector. The regenerative sustainability paradigm for the built environment was described by Du Plessis (2012). Du Plessis analyzed and contextualized the role of regenerative design in a historic perspective. While conventional sustainability consists in limiting the impacts over the environment by giving back as much as it is taken, regenerative sustainability seeks to restore ecosystems to a healthy state and then developing a co-creative partnership with nature. The objective is to have a positive impact over the environment by following strategies based on adaptation, resilience and regeneration (Du Plessis, 2012). Mang and Reed started developing a framework for designers to successfully apply the regenerative concept to the build environment. Regenerative systems are place specific and the framework includes a requirement to 'build to place, not formula' (Mang and Reed, 2012).

The life cycle of buildings consists of different phases with different specificities that coexist within a complex equilibrium. Building construction, use phase, and end of life are major sources of environmental impacts. It is estimated that half of all extracted materials in Europe are used for building construction and use. Buildings are responsible for around 40% of the total carbon emissions in the world, considering contributions from the production process of the materials, the construction of the building, and its operational phase (Baldassarri et al., 2017). Research on the Life Cycle Assessment (LCA) of buildings has

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Nomenclature

LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
CLT	Cross-laminated timber
IEA	International Energy Agency
ACE	Architecture, construction and Engineering
XPS	Extruded polystyrene
DHW	Domestic hot water
EN	*Europäische Norm* ("European Norm")
IPCC	Intergovernmental Panel on Climate Change
GWP	Global Warming Potential
CED	Cummulative Energy Demand
EF	Environmental Footprint
NMVOC	Non-methane volatile organic compounds
CTUh	Comparative toxic unit for human
CFC11	Trichlorofluoromethane
U-235	Uranium-235
kBq	kilobecquerel
Pt	Dimensionless unit for some LCA calculations
H+	Hydrogen ion
Depriv	Deprivation
HVAC	Heating, ventilation, and air conditioning
HEMS	Home Energy Management Systems

been conducted for over 20 years and it is becoming the staple tool for analyzing the environmental performance of buildings (Bahramian and Yetilmezsoy, 2020) (Lützkendorf, 2018). Currently, the number of studies that analyze the LCA of buildings is growing (Hossain and Marsik, 2018) (Röck et al., 2018) (Abd Rashid et al., 2017). Also, due to the increasing popularity of cross-laminated timber (CLT) buildings, several studies are now assessing the environmental impacts of residential buildings using that material (Jayalath et al., 2020). Studies on how to successfully build passive houses in different climate zones have already been published (Schnieders et al., 2015) (Yong et al., 2017). However, the differences between the entire life cycle of a wood house in different locations in Europe have not yet been assessed, to our knowledge. It is well stablished that the operational phase of buildings is responsible for the largest share of energy consumption in the entire life cycle (Gustavsson et al., 2010). A recent study conducted by the International Energy Agency (IEA) states that the building sector, including residential and services had the largest increase in energy use (International Energy Agency, 2021). Moreover, the U.S. Energy Information Administration projects that global energy consumption in buildings will grow by 1.3% per year on average from 2018 to 2050 (U.S. Energy information administration, 2019). Due to the regional conditions in each location, the energy demand during the operational phase naturally varies. As more is understood about the impact of buildings at all life cycle phases and for all types, the concept of regenerative sustainability is gaining popularity in the building sector (Zhang et al., 2015) (Eberhardt et al., 2019). The concept has even been applied to optimizing urban design (Natanian and Auer, 2020). The challenges that the transition towards a regenerative paradigm represent have also been studied through case studies (Attia, 2016), (Aksamija, 2016). However, there is a lack of consistency on show the strategies should be adapted to different climates.

This study deals with the analysis of the existing barriers as well as the opportunities in the design process of a single-family wooden house with regenerative sustainability goals in the European context. By using the same house design and components it is possible to better analyze how those barriers change exclusively because of the local conditions (i.e., to consider place in a regenerative framework from an impact assessment perspective). Understanding those changes could help in designing better and more optimized buildings.

The objectives of this study were to better understand the environmental impact of single-family wood homes and determine how to improve their design to reach higher sustainability goals given the environmental and energy mix contexts of their location. To achieve these objectives, cradle to grave LCAs of a representative single-family wood-framed house located in five cities in Europe were performed and compared. The locations chosen have both similar and differing climate conditions and different power generation mix. This mix of similar climate conditions and differing energy mixes supports examining the interlink and affect the overall environmental impacts in a given place. The environmental impacts were compared to determine the barriers and opportunities for regenerative construction. By using an adequately insulated wooden house, it is possible to observe how far current practices are from regenerative sustainability. The results can be useful to architecture, construction, and engineering (ACE) professionals in understanding optimizing building design for better environmental performance and for researchers to target their activities on solutions that improve environmental impacts.

2. Materials and methods

A single house design was used and set in five different European cities, Munich, Ljubljana, Portorož, Madrid, and Valencia. The first two cities have continental climates, and the last three Mediterranean climates. Although only two climatic zones were covered, each location has specific characteristics leading to differences in weather conditions, material sources, electricity mix, and use patterns between all locations. Choosing locations with similar weather conditions and from different countries makes possible to analyze the influence that factors such as the electricity mix and the climate conditions have over the total environmental impacts of a house in different parts of Europe. A summary of the average temperatures at each location as well as the heating and cooling degree days is reflected in Table 1.

A building designed to represent an average European single-family wood house was used as a reference for the study (Schau et al., 2019). Wood was used for the frame due to its lower carbon emissions compared to concrete (Guardigli et al., 2011). The rest of the building elements consist of conventional materials specified in subsequent sections.

The study implements cradle to grave Life Cycle Assessment (LCA) of the reference house at the five locations. An energy simulation was carried out to analyze the use phase, obtaining the consumption at each location.

2.1. Description of the building

The model European reference house is a two-story house with a gable roof conceived to represent the average single-family detached

Table 1
Summary of the weather conditions in each location ("Weather Spark," 2021) ("Heating & Cooling Degree Days - Worldwide data calculation," 2020).

	Hot season temperature (°C)		Cold season temperature (°C)		Heating degree days (15 °C)	Cooling degree days (18.3 °C)
	High	Low	High	Low		
Ljubljana	27	15	3	−3	3165	137
Madrid	33	18	10	0	1860	596
Munich	24	13	3	−4	3730	47
Portorož	29	18	9	1	1789	505
Valencia	30	22	16	6	1024	627

home in Europe. The structure consists of wood, and the building envelope is insulated with several layers of mineral wool to minimize thermal losses. The two biggest façades face north and south, respectively. The north façade has a minimum number of openings to maximize thermal insulation. The first floor is mainly the living/social zone, where there is a living room, kitchen, a storage room, a study, and a small toilet. The second floor is the private/sleeping zone containing two small bedrooms, one master bedroom, and a bathroom. The building plans can be found in Figs A1-A8 in the Appendix section and a summary of the building plan is depicted in Fig. 1.

2.1.1. Building layers

The base building layers were selected because they are available in all locations and allow the house to be more comparable between locations. The same thermal insulation was used in every location to allow direct comparison of the relation between the climate conditions and the energy consumption. Comparing the performance of the exact same building in different locations is critical to allow the results to be extrapolated and comparable. By using the same building the influence aspects such as climate change have over the life cycle of the building are easily identifiable. The building envelope is highly insulated (Table 2). The materials used in each building layer are specified in Tables A1-A9 in the Appendix section. The walls and the roof are insulated with stone wool. The ground floor combines extruded polystyrene (XPS) with a thinner layer of stone wool as XPS is more suitable than mineral wool to be exposed to the moist conditions on the ground floor. Detailed sections of the building envelope can be found in Figs. A9 to A12 in the Appendix section. The purpose of this design is to minimize the amount of energy needed for heating and cooling. The transmittance of the building envelope was adjusted to comply with building regulations across Europe in the year 2020 ("Zebra, 2020. Energy efficiency trends in buildings," 2020). Given the fact that the lower the U-value of a building element, the more insulating it is, the U-values are in all cases within required by each national legislation. In the case of Germany and Slovenia, the U-values of the building elements used meet the requirements established by their national legislation by a slim margin. In Spain, the building code updated in 2020 the requirements for building efficiency lowering the minimum U-value required to comply with the regulation. The U-values of the exterior walls need to be lower than 0.28 W/m^{2}K in Slovenia, 0.20 W/m^{2}K in Germany, and 0.29 W/m^{2}K in Spain. The maximum U-Value for flat roofs in Slovenia is 0.18 W/m^{2}K, 0.14 W/m^{2}K in Germany, and 0.23 W/m^{2}K in Spain. The building regulations of each country concerning energy efficiency were obtained from the database created by (Concerted action EPBD, 2020).

Table 2
Building envelope.

Building element	U-value (W/m^{2}K)	Surface area (m^2)
W1. Exterior walls	0.146	164.48
W2. Exterior wall ground floor bottom	0.262	22.42
R1 roof	0.132	123.42
F1 ground floor-ceramics	0.175	13.28
F1/A ground floor-ceramics in bathrooms	0.186	10.2
F2 ground floor parquet	0.174	76.52

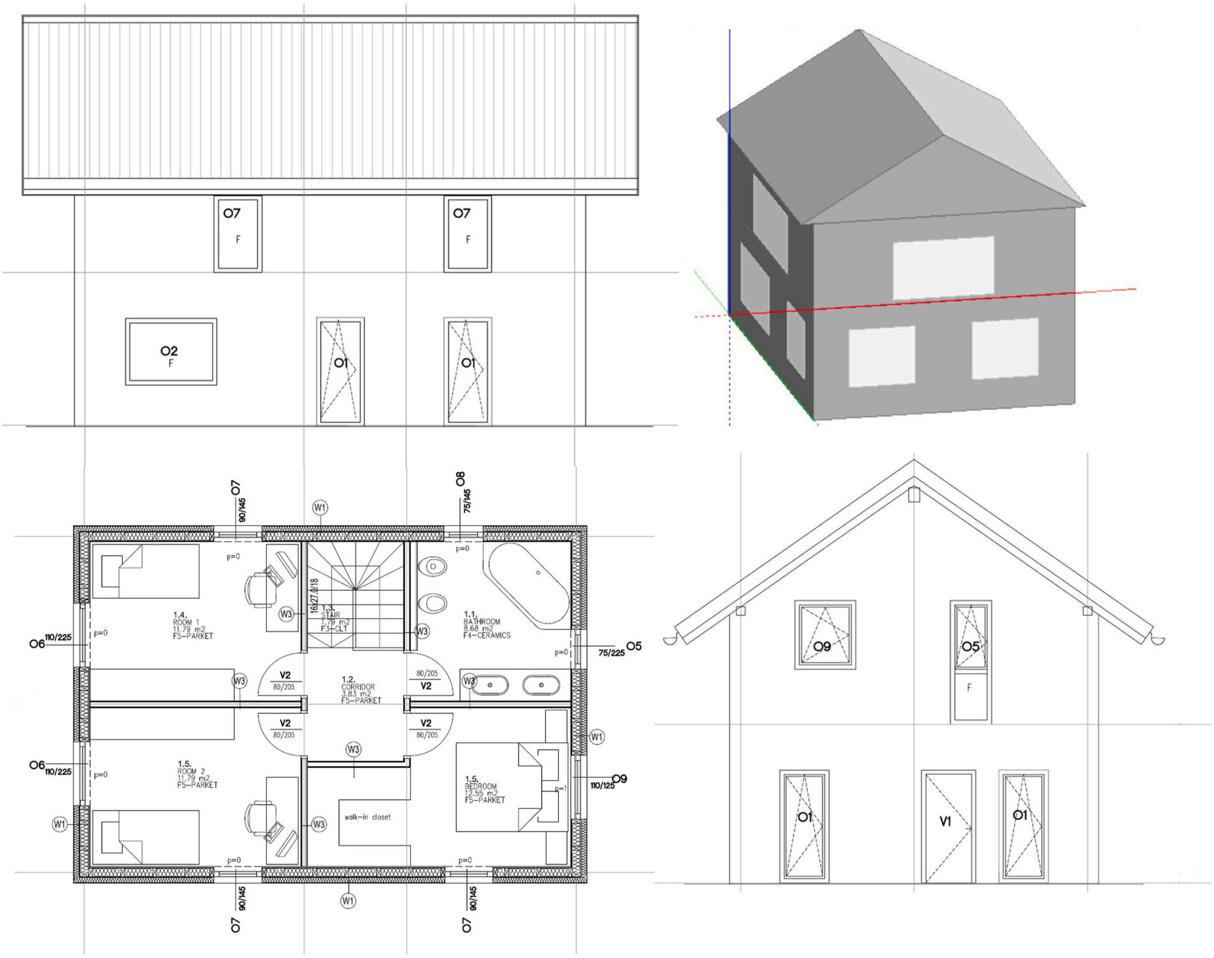


Fig. 1. Overview of the house plans.

2.2. Thermal simulation

To assess the environmental impacts of the house in each location it is necessary to know its energy demand. The amount of energy needed to maintain thermal comfort will vary considerably depending on the climatic conditions in each location. A simulation was run to calculate that energy demand. The building elements considered for the simulations are described in Table A1 to A9 in the appendix section.

The energy simulation software used was DesignBuilder 6.1, a well-recognized software tool for analyzing the energy demand in buildings (Design Builder, 2019). DesignBuilder uses EnergyPlus, developed by the US Office of Energy Efficiency & Renewable Energy (United States Department of Energy, 2019), as its calculation engine. The weather data was obtained from The American Society of Heating, Refrigerating and Air-Conditioning Engineers ("American Society of Heating, Refrigerating and Air-Conditioning (ASHRAE)," 2017), which is considered the standard for building performance simulation. The steady-state simulation calculates the energy consumption of the room electricity, lighting, heating, cooling, and domestic hot water (DHW). Electricity was used to cover the demand of all the end-uses except for heating, which was covered using natural gas. The activity and occupancy for the energy simulation was modeled using data from Eurostat (European Statistical Office, 2020). Electricity consumption for appliances and lighting was assumed to be equal in each location because of the small differences in the average consumption in the countries under study, according to the latest sectorial profile of the Odissee-Mure project (Odyssee-Mure, 2020). Accounting for the different impacts caused by electricity for appliances and lighting is a subject of great interest, yet outside the scope of this study.

2.3. Life cycle assessment

The LCAs were performed following the guidelines described in the ISO 14040:2006 (ISO 14040, 2006) and the EN 15804:2020 (European Committee for Standardization, 2020). The modules considered are A, product phase and construction process, B, use phase, and C, end of life. Considering the modules analyzed, this can be considered a cradle to grave LCA.

2.3.1. Functional unit

The functional unit in an LCA study refers to the element used as the comparative reference. In this case, the functional unit is the entire life cycle of the 100 m^2 large dwelling, considering a lifespan of one hundred years.

2.3.2. Allocation principle

The allocation principle used in this study is allocation at end-of-life (EoL) according to EN 15804:2020. The methodology was implemented following Baldassarri et al. (2017) and (Lavagna et al., 2018).

2.3.3. Life cycle inventory (LCI)

The software used to create the LCI was Simapro v 9.0. Simapro incorporates Ecoinvent V3.5, the most comprehensive database for LCA calculations (Wernet et al., 2016). The impacts generated by each material were adapted to the market in each location by using their country electricity mix. This is a realistic approximation due to the consistency in production technology among European countries. The electricity mix accounts for the different ways to produce energy in each country. Therefore, 1 kWh will have different impacts in each country under study. The electricity mix of each country in the study is described in Table 3. Factors such as the energy quality of each one of the sources are taken into account by the Life Cycle Inventory developed using Ecoinvent. The quality of an energy source can be understood as the ease in which that energy is utilized for a variety of end-uses (Dias and Pooliyadda, 2004).

Table 3
Electricity generation percentage. 2019 statistics (Eurostat, 2019) (European Environment Agency, 2020).

	Germany	Slovenia	Spain
Conventional thermal	56.0	30.8	42.2
Nuclear	12.6	35.9	20.4
Hydro	3.5	31.6	13.8
Wind	19.6	0.0	19.0
Solar	8.1	1.7	4.6
Geothermal & others	0.1	0.0	0.0
Kg of CO_2 eq. per kWh	0.406	0.248	0.276

As detailed in previous sections, the processes considered in the LCA are divided into modules, according to the guidelines of the EN 15804 (European Committee for Standardization, 2020) (Fig. 2).

Module A: this module contains all materials used for the main building elements (those elements are specified in Tables A1-A9 in the Appendix section). Transportation of the materials from the warehouse to the building site were considered to be taken from a 50 km distance. This approximation has been used in several LCA studies (Asdrubali et al., 2013). Other studies also assumed 50 km for massive materials and 100 km for the rest (Lavagna et al., 2018). The materials used for the heating and cooling systems have also been included in the inventory.

Module B: this module comprises the processes that take place during the use phase of the house. In this case, the processes considered are energy consumption and the materials required for maintaining the building. Data on the replacement intervals of building materials was found in literature (Baldassarri et al., 2017): 30 years for mineral insulation, 30 years for internal walls, 30 years for windows and 50 years for finishes. The energy required for heating is assumed to be natural gas. Electricity is used for the rest of the categories. The use of renewable energy sources such as solar panels is neither considered nor modeled in the energy simulation. Modelling how different renewable energy sources might alter the results is beyond the scope of this article. The lifespan of the house is assumed to be 100 years. Although the lifespan of buildings varies significantly, 100 years can be considered a realistic assumption (Lavagna et al., 2018), (Marsh, 2017).

Module C: at end-of-life, incineration is used to model the end of life of the wood used in the house, which is the most common waste management practice for timber products (Hafner et al., 2014). For the other materials, landfilling is selected as the most plausible scenario because approximately 85% the total construction waste is landfilled (UNEP, ISWA, 2015). The distance assumed for transportation to the landfilling and the incineration plant was 50 km (Wilson, 2007).

3. Results

3.1. Thermal simulation results

Fig. 3 shows the amount of kWh required each year divided into five categories: room electricity, lighting, heating, cooling, and domestic hot water (DHW). The energy expended to produce heat varies the most, followed by hot water production. Munich and Ljubljana use approximately eight times more energy for heating than Valencia, while Madrid uses only three times more energy for heating; Portorož uses approximately four times more energy for heating than Valencia. The energy used for cooling is significantly higher in Madrid and Valencia – approximately double that of Portorož – while it is negligible for both Ljubljana and Munich. Room electricity and lighting energy demands are constant based on the Odissee-Mure project (Odyssee-Mure, 2020). DHW varies slightly due the greater temperature differential between input water and hot water.

These LCA calculations were carried out using two different highly trusted methods. The first one is the IPCC GWP 100a method. Developed by the Intergovernmental Panel on Climate Change, this method calculated the amount of CO_2 equivalent (CO_2e) emissions using the 100-year time horizon ("IPCC - Intergovernmental Panel on Climate

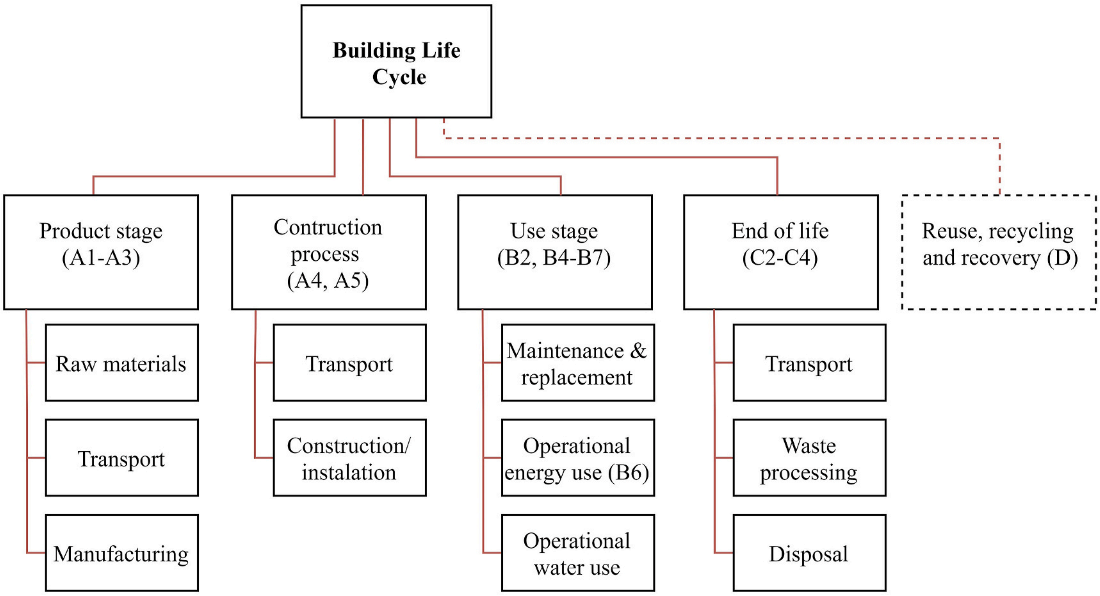


Fig. 2. Building life cycle (with modules A1-D) according to EN15804 (2020), Module D and module B3 (repair) are outside the scope of the study.

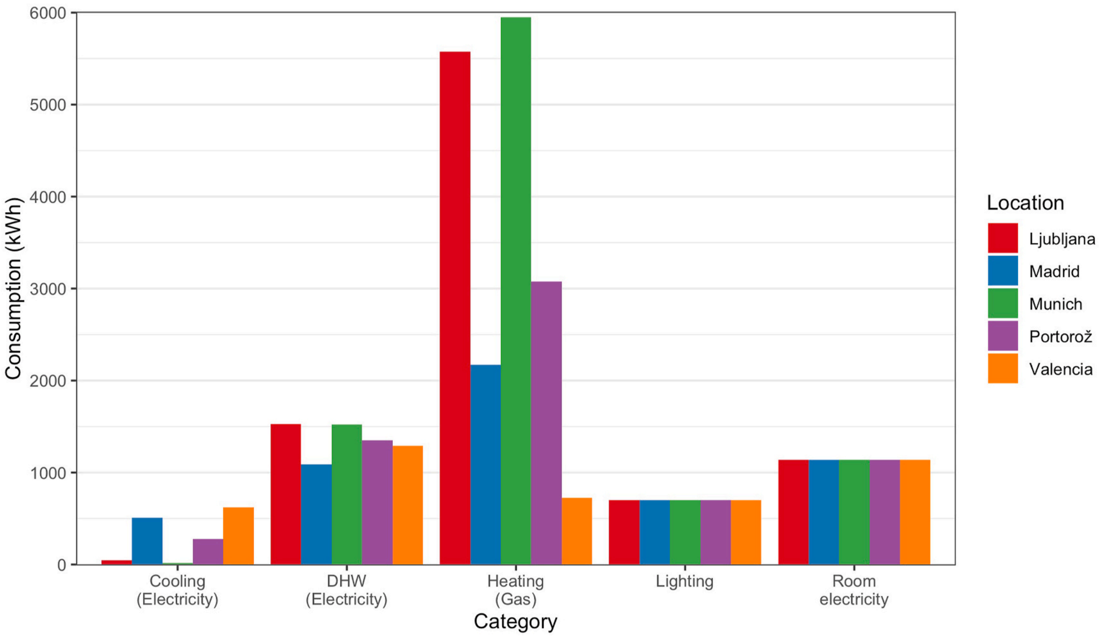


Fig. 3. Energy consumption (kWh) over a one-year period.

Change," 2020). The second method is the Environmental Footprint method (version 2) developed by the Joint Research Centre of the European Commission. This method is recommended to be used in the European Union (European Commission, 2013). Extensive documentation on the Environmental Footprint method as well as its normalization and weighting process of the results was developed (Zampori and Pant, 2019). Additionally, the cumulative energy demand method was used to obtain the embodied energy of the modules A1 to A5 and the module B6.

3.1.1. Module differences between locations

The networks representing the contribution of each module to the total carbon emissions in each location are represented in Figs. 4–8. The comparison between the carbon emissions is depicted in Fig. 9. The results show that the house located in Munich generates significantly more CO_2e than the rest. It generates 28% more CO_2e than the house in Ljubljana despite having a similar energy consumption. In Munich, energy consumption is responsible for 76.1% of the total greenhouse gas emissions over the life cycle. In Valencia, the location with the lowest energy demand, it is responsible for 63.7%. There is only a 12.4% difference between the two cities despite the energy consumption in Valencia being 50% lower. The difference between the CO_2e emissions in the Spanish and the Slovenian locations is also smaller than what the energy consumption might suggest. The fact that the house in Madrid has higher CO_2e emissions than the one in Portorož despite having a lower energy consumption also stands out. This is caused by the different energy sources in each country. Fig. 10 shows the cumulative energy demand (CED) of modules A1-A5 and B6. The CED of modules A1-A5 is almost the same in each location due to the extensive use of biomass and fossil fuels, which are not as sensitive to regional variability. In the case of module B6, there is a great variation between

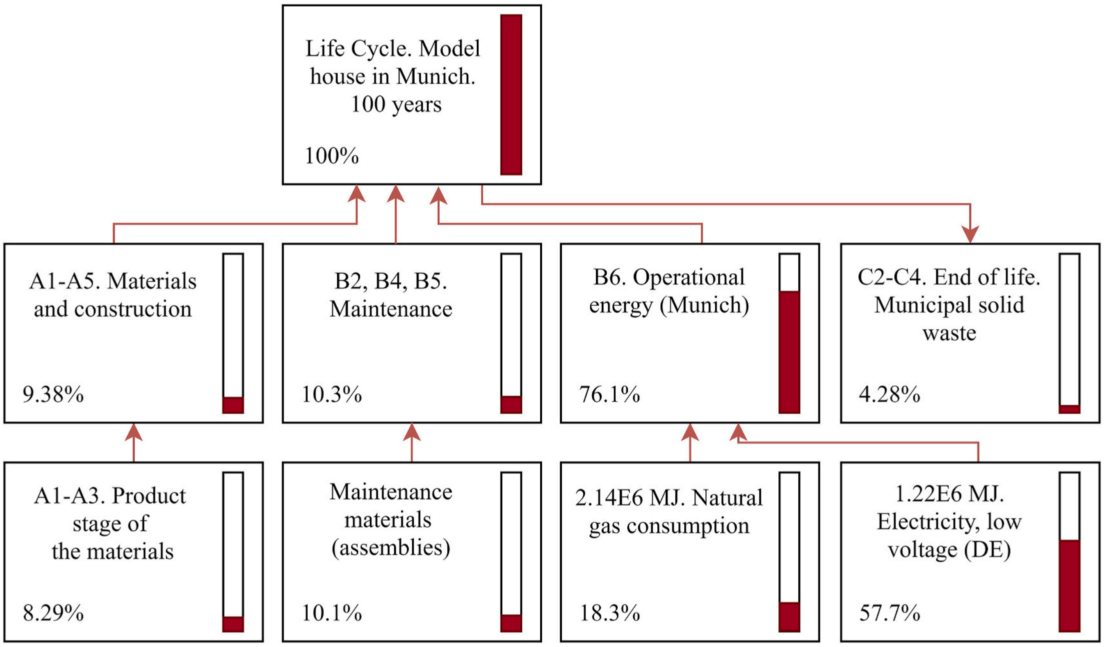


Fig. 4. Contribution of each module to the total carbon emissions in Ljubljana.

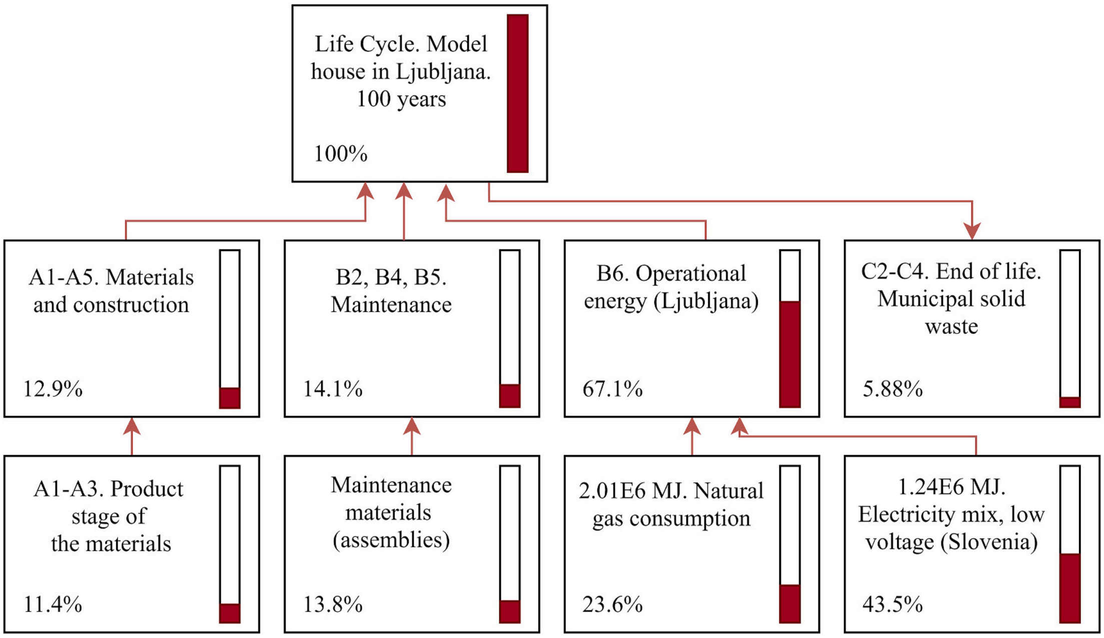


Fig. 5. Contribution of each module to the total carbon emissions in Madrid.

locations, which evidences the differences in the efficiency of energy generation. The effect of the electricity mix is further discussed in subsequent sections.

In addition to greenhouse gas emissions, other environmental impacts were evaluated using the Environmental Footprint method. The characterization results are divided into 18 different impact categories. The obtained results show similar tendencies to the previous method in categories like climate change, eutrophication, and acidification (Table 4).

In Fig. 11, the normalized results reveal high impacts related to human health and resource use for energy. After weighting the normalized results, the climate change potential and the use of energy gain importance and reveal Munich as the most impactful location (Fig. 12). Considering that the results are normalized and weighted, the EF offers the possibility of obtaining a single impact score result by adding up each category (Table 5). It should be noted, however, that climate change is highly weighted in the EF method, accounting for 21% of the total impact (including robustness factor) (Sala et al., 2018). As observed in the IPCC method, the impact score is significantly higher in Munich than in the other cities. In this case, the score obtained in Madrid is lower than the one in Portorož despite its higher climate change potential, due to the influence the other impact categories have.

3.1.2. Comparing the A1-A5 and energy consumption for cooling and heating between different cities

The calculations of the house's whole life cycle suggested that the

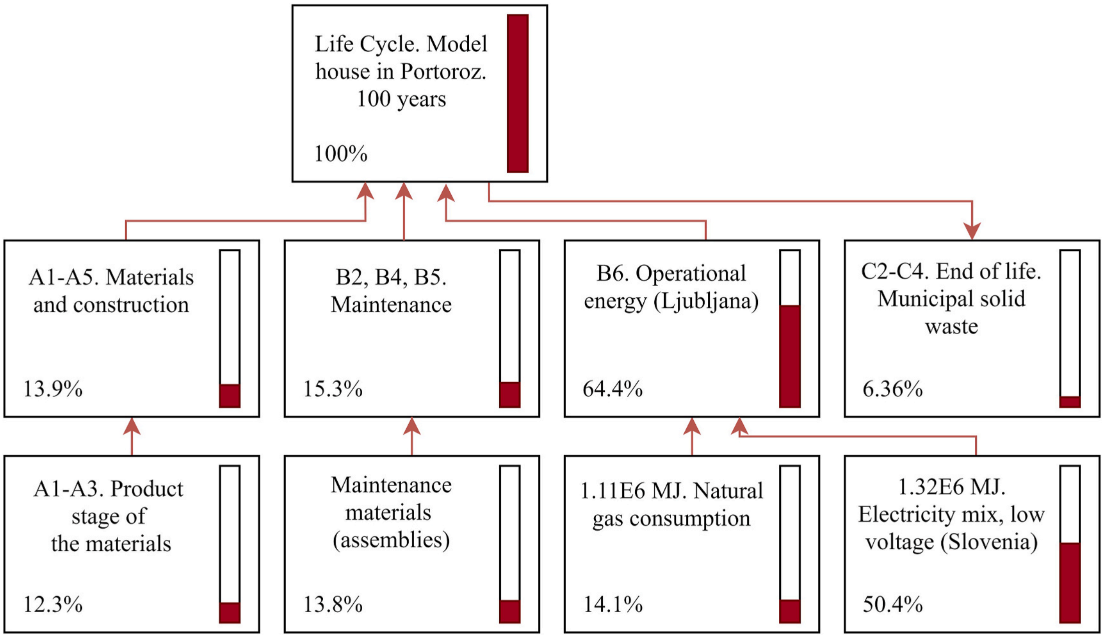


Fig. 6. Contribution of each module to the total carbon emissions in Munich.

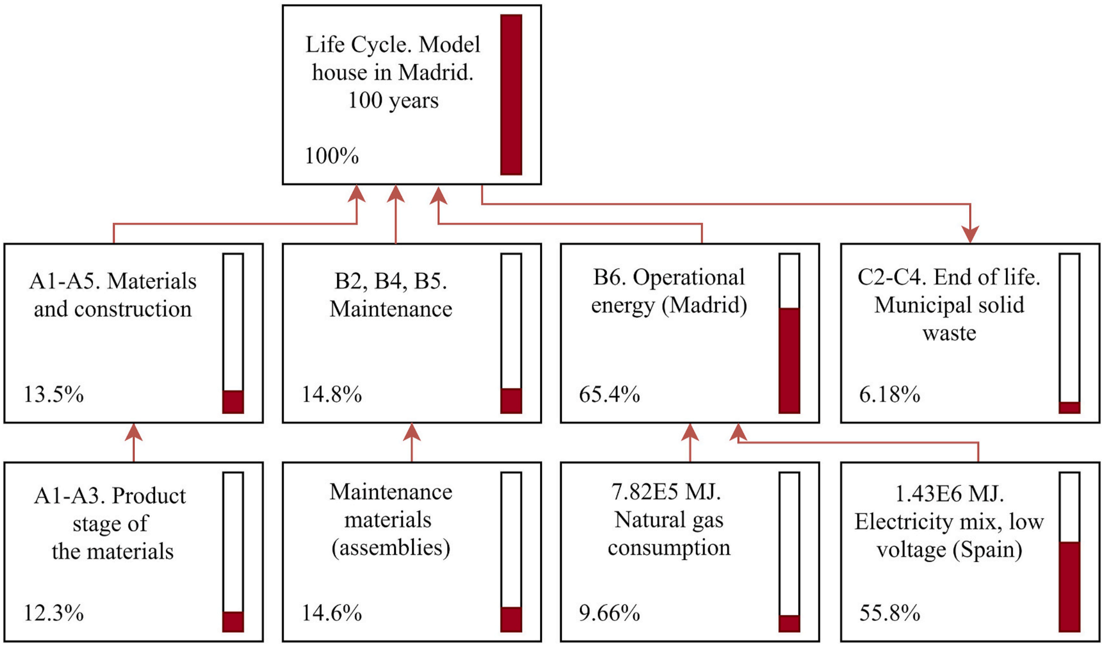


Fig. 7. Contribution of each module to the total carbon emissions in Portorož.

electricity mix of each country plays a big role in the total emissions of the house. As a way of checking if that is the case, the calculations have been performed again, considering only the modules A1-A5 (with the manufacturing of materials, transport, and construction/installation on site) and the energy use for heating (natural gas), ventilation, and air conditioning (HVAC) (part of module B). First, the carbon emissions are assessed again using the IPCC GWP and the EF method. As shown in Table 5, the differences between CO_2e emissions are directly related to the heating consumption in each city. Due to the use of natural gas for heating, the effect of the country's electricity mix is attenuated, only affecting the energy used for cooling. Using the EF method, the single score results follow a similar tendency as the ones obtained using the IPCC GWP except for Madrid and Valencia. In the case of the two Spanish cities, the impacts are higher due to the electricity consumption for cooling and the effect of the electricity mix. The total impact of the building at Portorož is almost the same as in Valencia, despite the

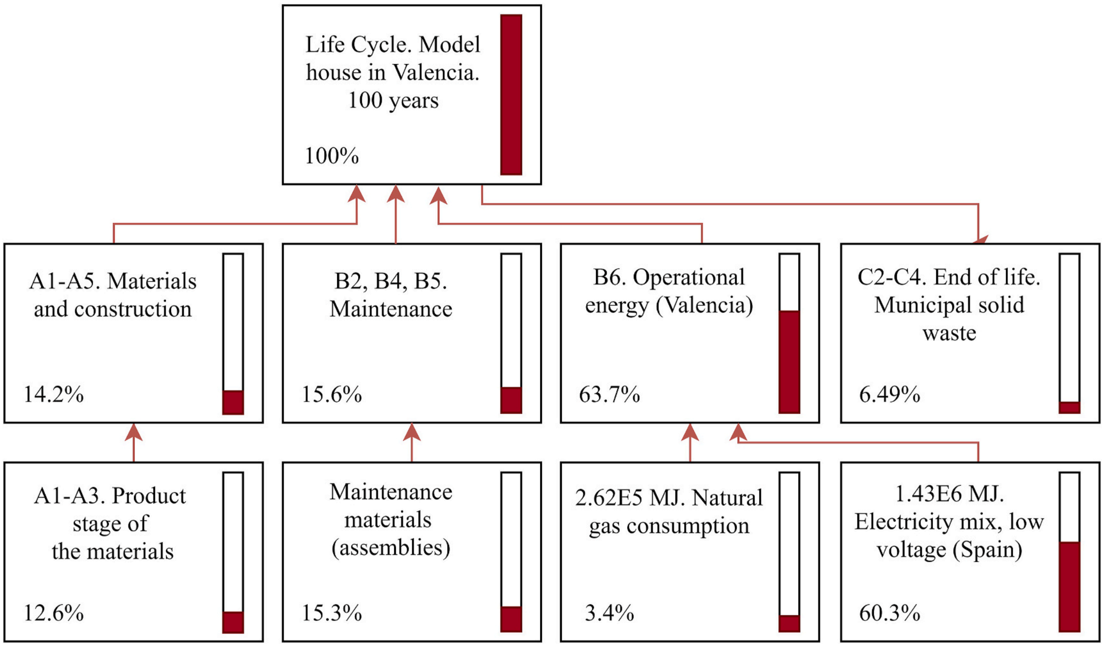


Fig. 8. Contribution of each module to the total carbon emissions in Valencia.

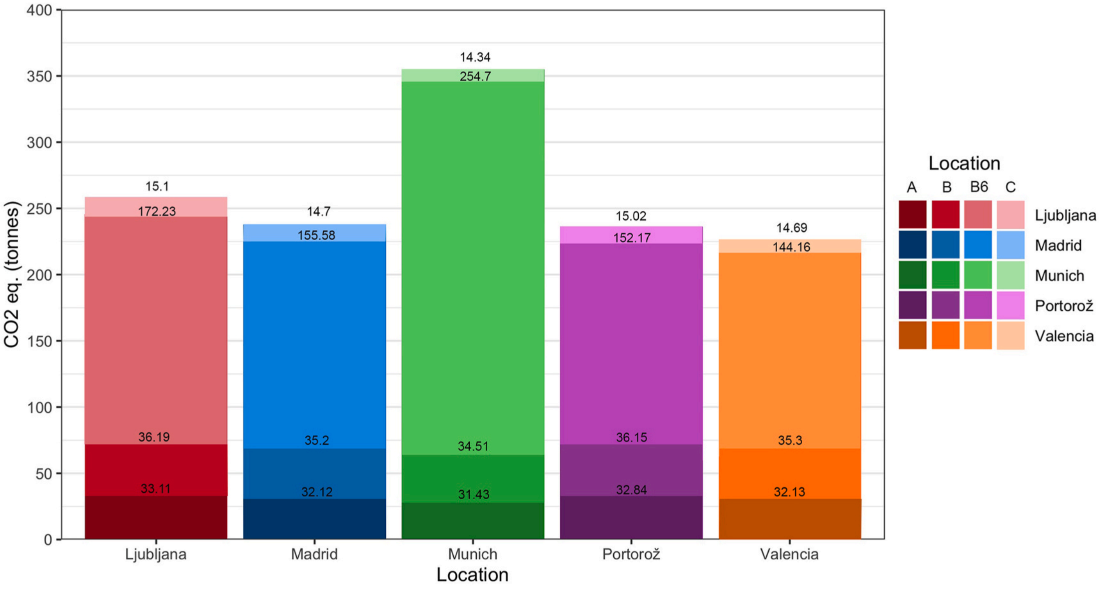


Fig. 9. IPCC GWP method, CO2 eq. emissions.

significantly lower energy requirement for heating. As it is analyzed in more detail in subsequent sections, these results show that the energy sources have a major influence over the overall environmental impacts.

4. Discussion

This study shows how the barriers between conventional construction and regenerative buildings change depending on factors linked to location - important aspect of place in the regenerative construction context. As it was expected, the carbon emissions associated with energy consumption (B6 Module) are the primary source of differences between locations. Due to the high CO_2e emissions of the B6 module, the share of impact contributed during each life stage of the house varies depending on the local climate (e.g., warmer in southern places and colder in northern places). Due to the higher CO_2e emissions of module B6 (operational energy use) in colder climates, the percent contribution of module A (product stage and construction process) is lower in locations with higher energy demand. Therefore, module A, with the same materials in an equivalent house, ranges from 9.38% in Munich to 14.2% in Valencia. The same tendency can be observed in module C (use phase). Despite the use phase contributing more to the total impacts in colder climates, energy consumption still is the main contributor in locations

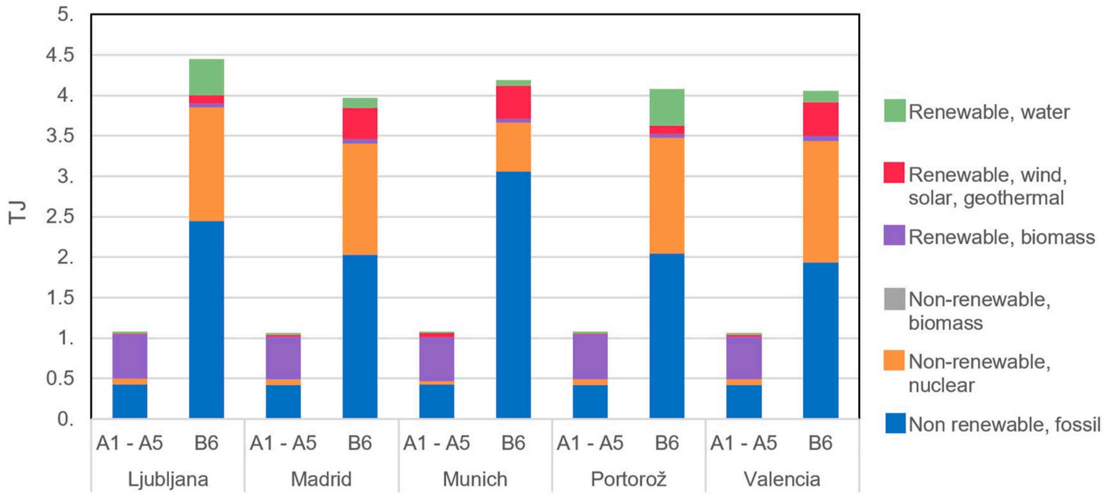


Fig. 10. Cumulative energy demand, A1-A5 and B6 (100 years).

Table 4
Environmental footprint characterization.

Impact category	Unit	Ljubljana	Madrid	Munich	Portoroz	Valencia
Climate change	t. CO2 eq	261.79	241.72	362.26	240.50	230.63
Climate change - fossil	t. CO2 eq	260.24	239.46	358.18	239.57	228.33
Climate change - biogenic	t. CO2 eq	0.82	0.59	3.31	0.75	0.60
Climate change - land use and transform.	t. CO2 eq	0.73	1.67	0.77	0.17	1.71
Ozone depletion	kg CFC11 eq.	2.33E-02	2.55E-02	2.31E-02	2.11E-02	2.43E-02
Ionising radiation, HH	kBq U-235 eq.	2.73E+04	3.47E+04	1.41E+04	2.89E+04	3.55E+04
Photochemical ozone formation, HH	kg NMVOC eq.	746.75	865.32	644.04	740.45	862.66
Respiratory inorganics	disease inc.	1.56E-02	1.52E-02	2.06E-02	1.57E-02	1.52E-02
Non-cancer human health effects	CTUh	2.74E-02	3.15E-02	3.09E-02	2.79E-02	3.18E-02
Cancer human health effects	CTUh	4.42E-03	4.20E-03	4.14E-03	4.50E-03	4.22E-03
Acidification terrestrial and freshwater	mol H+ eq.	2.74E+03	1.84E+03	2.05E+03	2.86E+03	1.86E+03
Eutrophication freshwater	kg P eq.	27.60	14.45	38.62	29.04	14.66
Eutrophication marine	kg N eq.	196.56	262.82	209.72	197.81	264.67
Eutrophication terrestrial	mol N eq.	3.08E+03	3.31E+03	6.62E+03	3.14E+03	3.33E+03
Ecotoxicity freshwater	CTUe	2.05E+05	2.01E+05	2.04E+05	2.02E+05	1.99E+05
Land use	Pt	1.22E+07	1.26E+07	1.29E+07	1.23E+07	1.27E+07
Water scarcity	m3 depriv.	6.08E+04	1.03E+05	5.69E+04	6.29E+04	1.06E+05
Resource use, energy carriers	MJ	4.37E+06	4.31E+06	4.78E+06	4.16E+06	4.17E+06
Resource use, mineral and metals	kg Sb eq.	0.96	1.03	1.07	0.97	1.03

like Valencia. This reinforces the need to use sufficient thermal insulation in warmer climates as well. It is also worth noting that Valencia is the only city where most energy is not used for heating. In this case, around 30% of the energy is used for warming water. Installing a solar DHW system would have a significant effect in reducing the energy consumption depending on the efficiency of the equipment installed, especially in countries with high solar irradiance such as Spain. However, the analysis of the savings generated with renewable sources is outside the scope of this study.

However, other factors can sometimes overshadow the local climate conditions. This is the case of the country electricity mix, which plays a critical role in the environmental impacts over the entire life cycle. By comparing locations with similar climate conditions with others that have considerably different ones it has been possible to analyze how the energy demand and the sources of energy interlink and affect the overall environmental impacts. For example, the 12.4-point difference in total greenhouse gas emissions between Munich and Valencia, while significant, is small when considering that the annual energy consumption is around 50% higher in Munich. It can also be highlighted that, despite the energy consumption in Munich only being around 4% higher than in Ljubljana, the house in Munich generates 28% more CO_2e over its entire life cycle. This is caused by the different sources of energy used to produce electricity in each country. As shown in Table 3, Germany generates almost double of its energy in combustion power plants than Slovenia. Similarly, despite the energy consumption being 10% lower in Madrid, the CO_2e are slightly higher than in Portorož. The fact that 42.2% of the energy in Spain is generated in combustion-based power plants is the most plausible explanation. It also explains why the difference between the emissions in Valencia and the Slovenian locations are not bigger despite the difference in energy consumption. The fact that Slovenia uses a higher percentage of nuclear energy also influences the results beyond carbon emissions. Categories like “Cancer human health effects” and “Acidification terrestrial and freshwater” obtain higher impact scores in both Slovenian locations. It is clear then, that national and regional level decisions about energy sources greatly affect the emissions and the overall environmental impacts generated in buildings. This will be a barrier for regenerative buildings as long as they are dependent on electricity from the grid. Strategies to overcome this

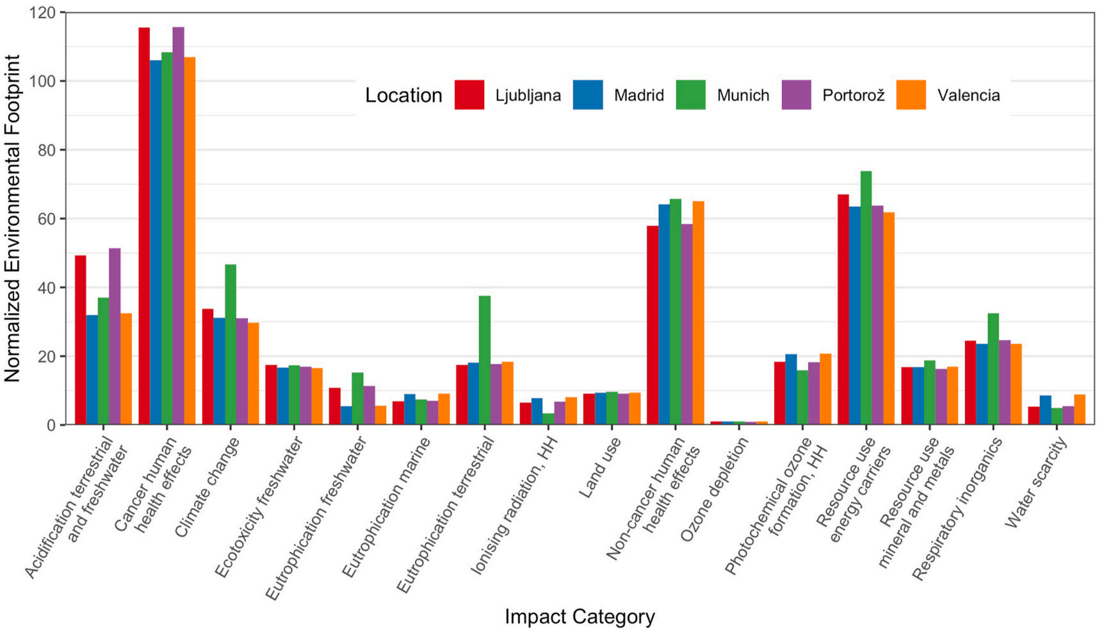


Fig. 11. Environmental Footprint normalization.

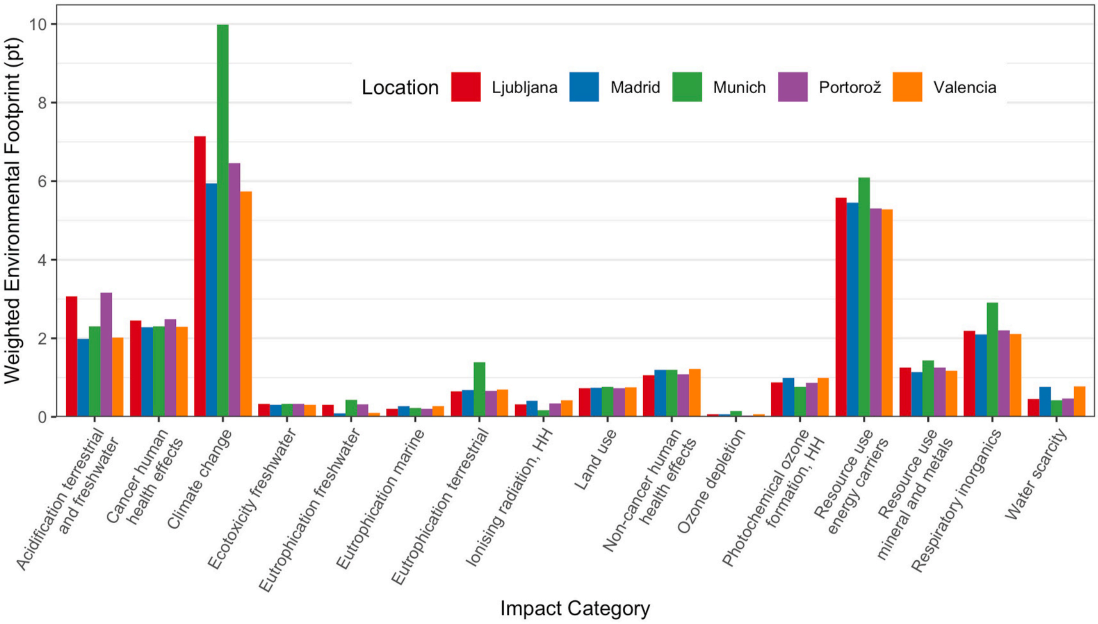


Fig. 12. Environmental Footprint weighting.

Table 5
Summary of the LCA impact results.

Location	Total EF single score (pt)	Total GWP (tonnes of CO$_2$e)	A1-A5 and HVAC. EF single score (pt)	A1-A5 and HVAC. GWP (tonnes of CO$_2$e)
Ljubljana	26.67	256.69	8.93	110.13
Madrid	24.98	237.90	8.65	89.74
Munich	30.68	355.13	9.06	113.84
Portorož	25.97	236.30	8.37	90.70
Valencia	24.68	226.31	8.23	78.12

barrier are opportunities for significant energy consumption reductions. For example, new policies designed to mitigate climate change should enforce the use of renewable energy sources for electricity production, thereby greening the building life cycle. Increasing the use of renewable energy would likely reduce the CO$_2$e emissions in all locations, and potentially reduce other indicators related to health (e.g., cancer, acidification). Therefore, considering its sizeable effect on the environmental impacts of buildings, the electricity mix can be considered one of the most important barriers towards regenerative architecture.

It is well known that thermal insulation is another key to reducing the energy demand of buildings. However, despite the sizeable amount of thermal insulation used in the model house, the energy required for heating and cooling still is quite high. These results suggest that passive isolation is not enough to design net-positive buildings. Besides increasing passive insulation and using sustainable materials such as wood, it is crucial to install efficient HVAC systems to lower the energy consumption to the minimum. Replacing conventional natural gas-powered heating systems with more efficient technologies such as air to water heat pumps would lead to a reduction in the overall impacts (Bellos and Tzivanidis, 2017) (Slorach and Stamford, 2021). The CO_2e emissions of the model house would be minimized in those locations where the electricity mix does not depend on fossil fuels. Moreover, due to the European Green Deal (European Commission, 2019), HVAC systems powered by electricity will become more sustainable in the future as energy generation transitions towards renewable sources. Despite this clear trend of transitioning towards renewable energy generation in the EU, the new European green deal will not reach its ultimate goal until 2050 (European Commission, 2019). Energy optimization becomes crucial to overcome the situation. Solution at the building level includes installing renewable energy generators such as solar panels and wind turbines to make the building more independent from the regional and national electricity mix. Also, great opportunities arise from the rapid development of home management systems technologies. Nowadays it is easier and more affordable to install equipment designed for fostering efficient management of domestic energy consumption. The use of these technologies could be the cornerstone of achieving regenerative sustainability goals, at least while conventional electricity generation relies on fossil fuels and nuclear energy. However, the high installation cost of some of these alternatives is an important barrier to entry for much of the population.

For the end of life, only incineration and landfill were considered. Module D with reuse, recycling, and (energy) recovery is outside the scope, but it is widely recognized that including this module would lower the total carbon footprint and other environmental impacts (Benachio et al., 2020) as the materials from the building could be reused or recycled into new products as well as heat and eventually electricity from incineration could be used to reduce other energy production. This strengthens our arguments that the use phase, and especially the energy use (B6), with its electricity consumption, is crucial for the overall life cycle of the house in different locations and represents a barrier for regenerative sustainability.

Finally, there is climate resiliency. Researchers elaborated on the probable changes that major cities in Europe will undergo in the near future. Their results indicate a foreseeable tendency of cities moving south climate-wise at a rate of 20 km per year (Bastin et al., 2019). Which might lead, for example, to the climate of Munich becoming similar to the current one in Ljubljana and the one in Portorož approaching the Valencian climate (cf., Table 1). For that reason, thermal insulation against extremely high temperatures will become crucial for cities such as Madrid and Valencia.

5. Conclusions and outlook

This study analyzed the existing barriers when designing regenerative houses by analyzing the cradle-to-grave LCA of a single-family wood house in five different locations in Europe. The locations were chosen with the purpose of analyzing the role that the relation between climate and country electricity sources play in the environmental impacts over the life cycle of the building. Several conclusions can be drawn after completing the study:

- The differences in the total environmental impacts between cooler and warmer locations were lower than anticipated. Despite the huge difference in energy consumption for space heating, the CO_2e emissions are only 35% lower in Valencia than in Munich. This is even more noticeable in Valencia and Ljubljana, where there is only a 10% difference.
- The country electricity mix can overshadow the effect of the energy demand. This is the case of the small difference between Valencia and Ljubljana mentioned before, but also in the case of Munich and Ljubljana. Despite Munich and Ljubljana having almost the same energy consumption, the CO_2e emissions of Ljubljana are 28% lower. This can also be observed in the results of Madrid and Ljubljana, where Madrid emits around 3% more CO_2e over its life cycle despite having a 30% lower space heating energy demand. These results put the focus on how important it is to strive for cleaner sources of energy. This indicates significant national and international level changes in energy production may be the most effective solutions to the climate impact of buildings. This is a critical consideration if the ecological transition supported by the European Green deal should be complete by 2050.
- Increasing the passive insulation is not enough to design net-positive buildings. The results indicate that even in locations such as Valencia and Madrid where the passive insulation greatly surpasses the requirements of the local legislation, the HVAC demand continues to be a great source of environmental impacts. Also, insulation does not have an effect on lowering the energy demand for DHW, room electricity, and lighting.
- Replacing concrete with a timber frame is not enough to sufficiently lower the environmental impacts of the building materials. Building and construction still represent more than 10% of the carbon emissions in all locations but Munich. While the use of wood for the frame is a wise choice to lower the environmental impacts of buildings (when forests are managed responsibly), using other biobased materials for the rest of the building elements would make a difference in lowering the environmental impact of the house.
- More extreme measures would need to be taken to achieve regenerative sustainability. The use of more efficient HVAC systems, such as air to water heat pumps, and the implementation of Smart Home Management Systems would help in optimizing the energy consumption. Also, renewable energy generators would be instrumental in cases where the local conditions allow them to be installed.

In future studies, the impact of replacing the materials in the building envelope with renewable alternatives will be studied. The materials in the building envelope have an influence that goes beyond the building phase (A module). The materials chosen also influence the maintenance phase (modules B2, B4 and B5) and module B6. Reuse, recycling, and recovery (Module D) were outside the scope of the current study. However, a wooden house has a large potential for material cascading where the materials are reused, recycled, or incinerated for energy recovery. This potential should be further researched to determine optimal end of life strategies for wood-based construction. Further research could focus on this, to understand how the environmental impact of the material of original house could be shared with other subsequent houses or other products made from the (demolished, original) house after its first functional life.

Disclosure statement

No potential conflict of interest was reported by the authors.

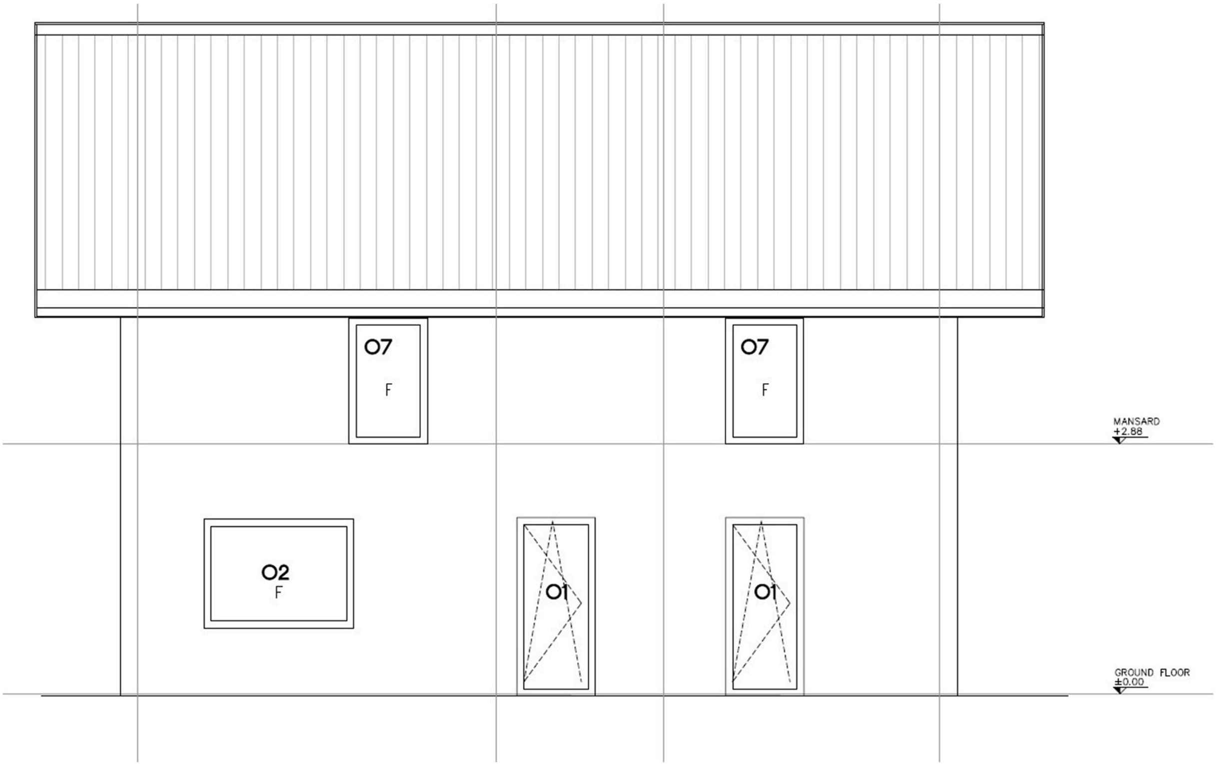

O7
F
O7
F
MANSARD
+2.88
O2
F
O1
O1
GROUND FLOOR
±0.00

Fig. A1.

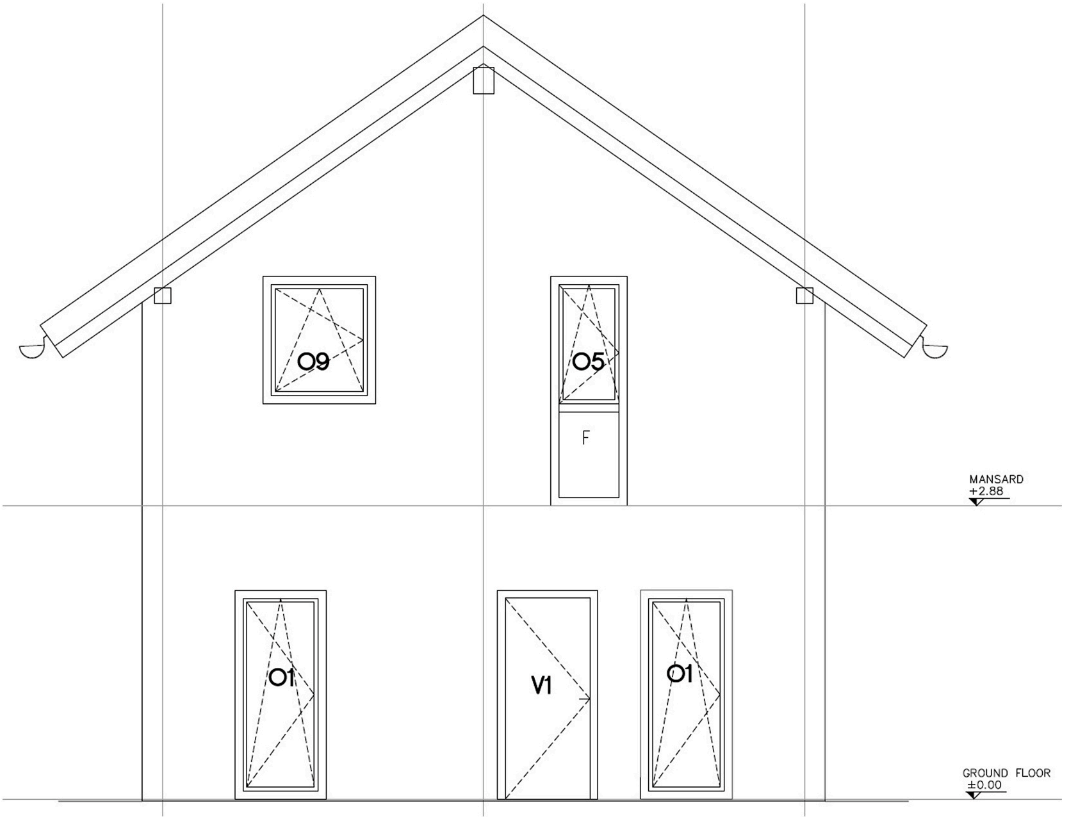
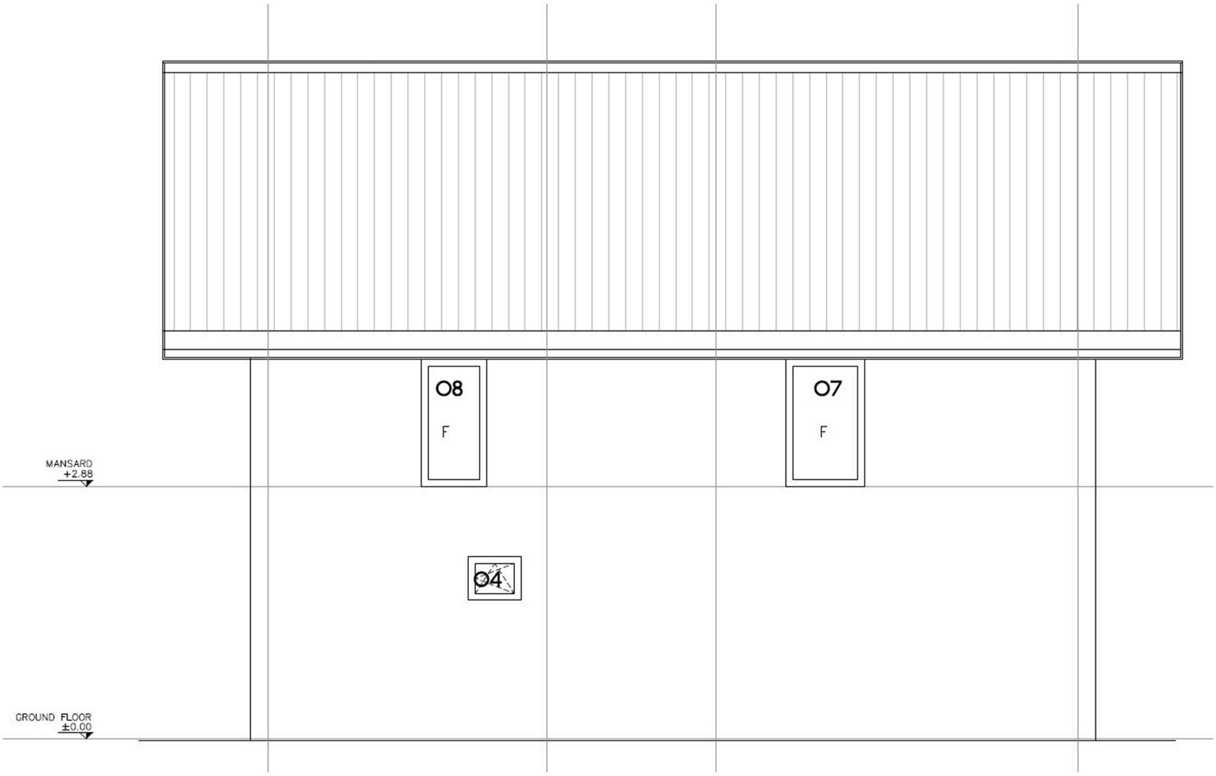

O9
O5
F
MANSARD
+2.88
O1
V1
O1
GROUND FLOOR
±0.00

Fig. A2.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O7
F
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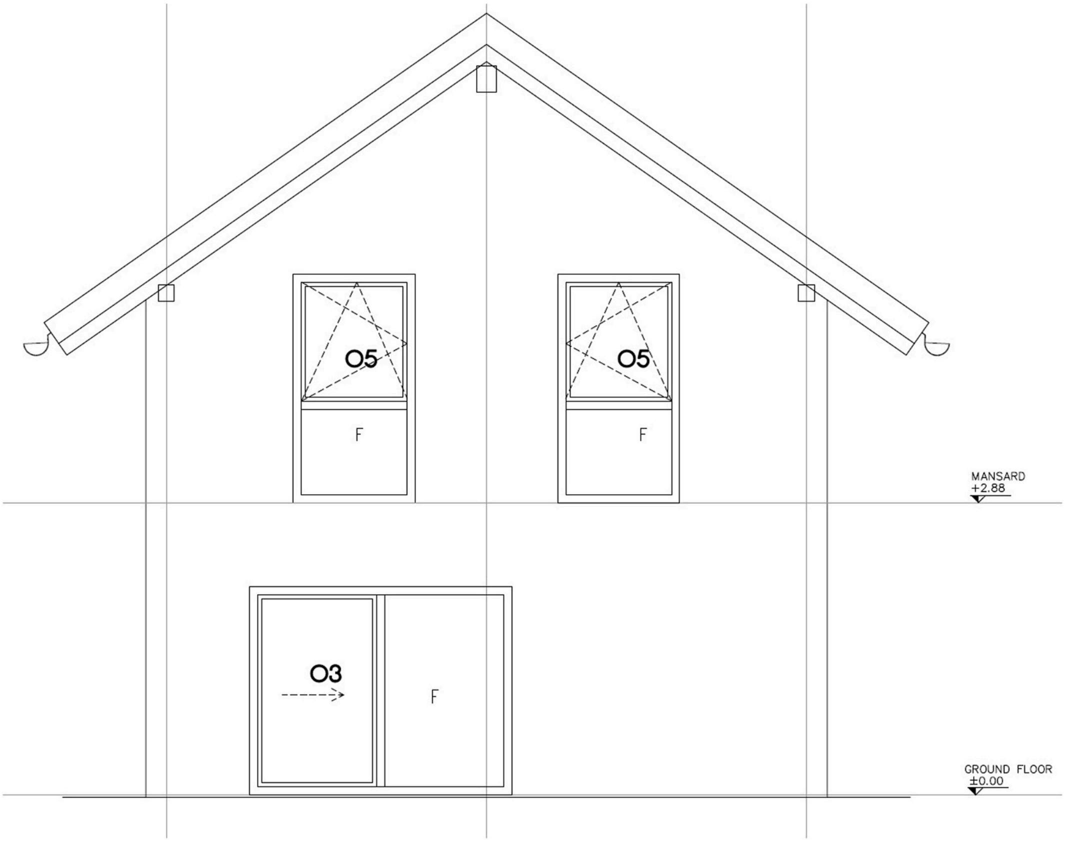
O4
GROUND FLOOR
±0.00

Fig. A3.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O5
F
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+2.88
O3
F
GROUND FLOOR
±0.00

Fig. A4.

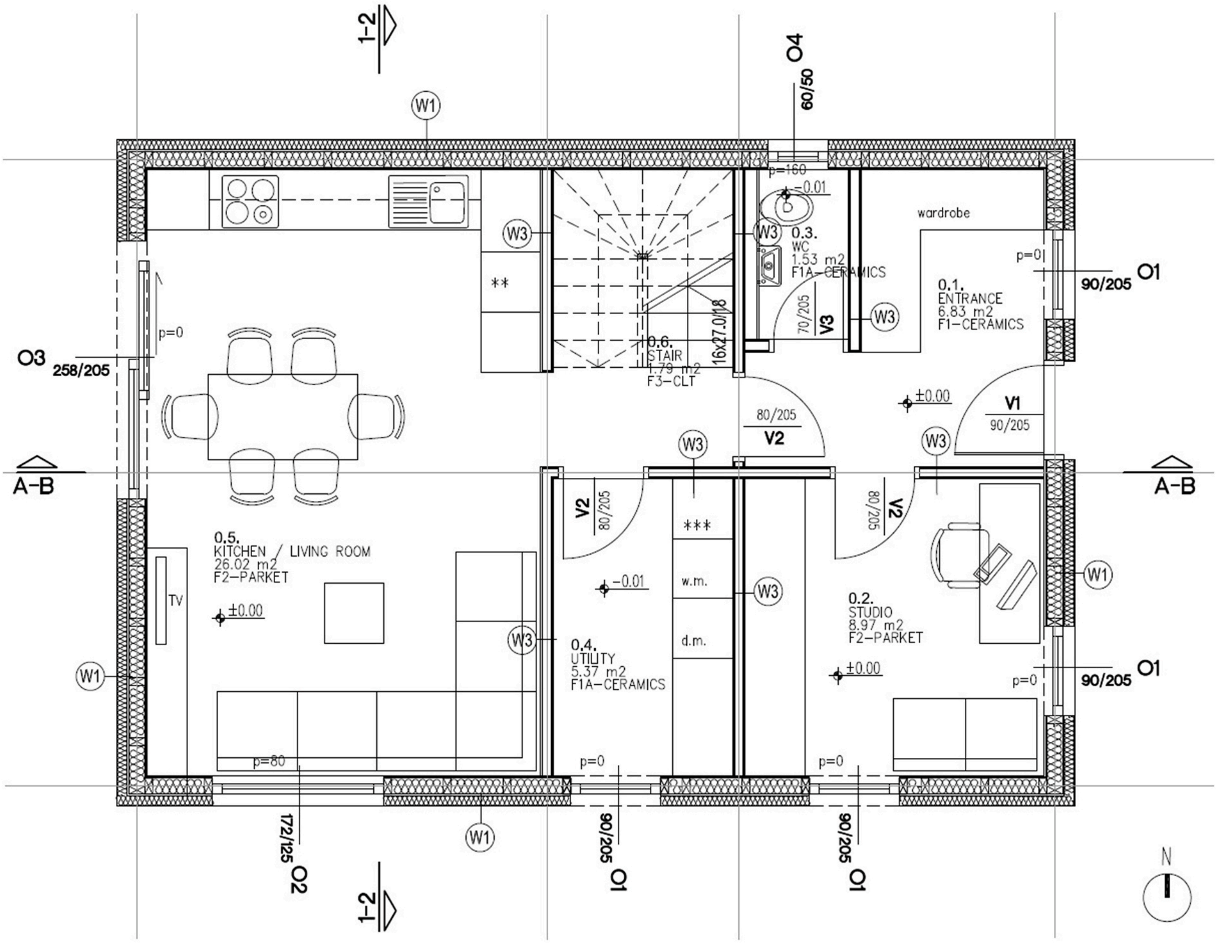
1-2
W1
O4
60/50
p=160
-0.01
W3
0.3.
WC
1.53 m2
F1A-CERAMICS
wardrobe
p=0
90/205
O1
0.1.
ENTRANCE
6.83 m2
F1-CERAMICS
70/205
V3
**
0.6.
STAIR
1.79 m2
F3-CLT
16x27.0/18
O3
258/205
p=0
±0.00
V1
90/205
80/205
V2
A-B
***
w.m.
d.m.
-0.01
0.5.
KITCHEN / LIVING ROOM
26.02 m2
F2-PARKET
TV
±0.00
0.4.
UTILITY
5.37 m2
F1A-CERAMICS
0.2.
STUDIO
8.97 m2
F2-PARKET
±0.00
p=80
p=0
172/125
O2
N

Fig. A5.

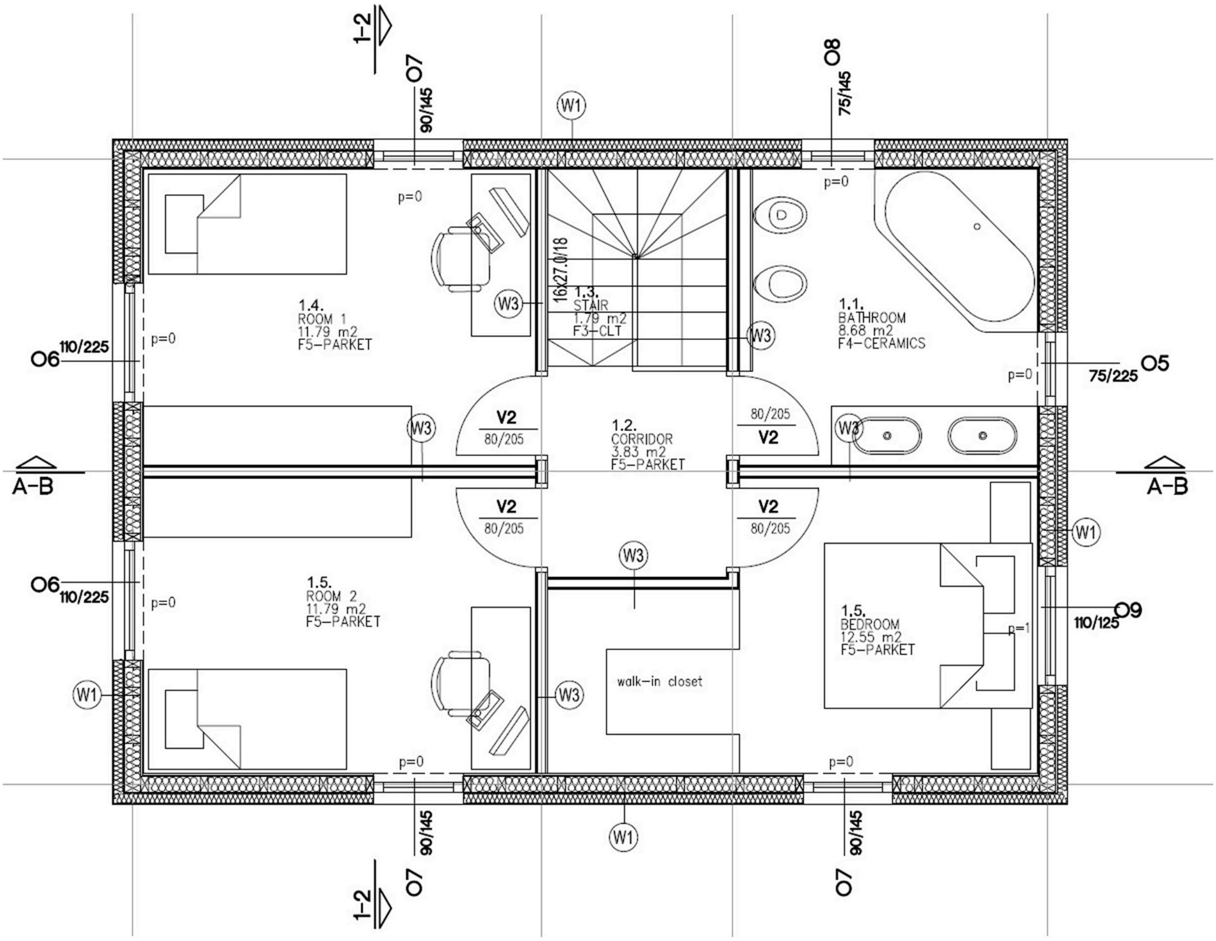
1-2
O7
90/145
W1
O8
75/145
p=0
1.4.
ROOM 1
11.79 m2
F5-PARKET
W3
16x27.0/18
1.3.
STAIR
1.79 m2
F3-CLT
1.1.
BATHROOM
8.68 m2
F4-CERAMICS
O6
110/225
O5
75/225
V2
80/205
1.2.
CORRIDOR
3.83 m2
F5-PARKET
A-B
1.5.
ROOM 2
11.79 m2
F5-PARKET
walk-in closet
1.5.
BEDROOM
12.55 m2
F5-PARKET
O9
110/125
p=1

Fig. A6.

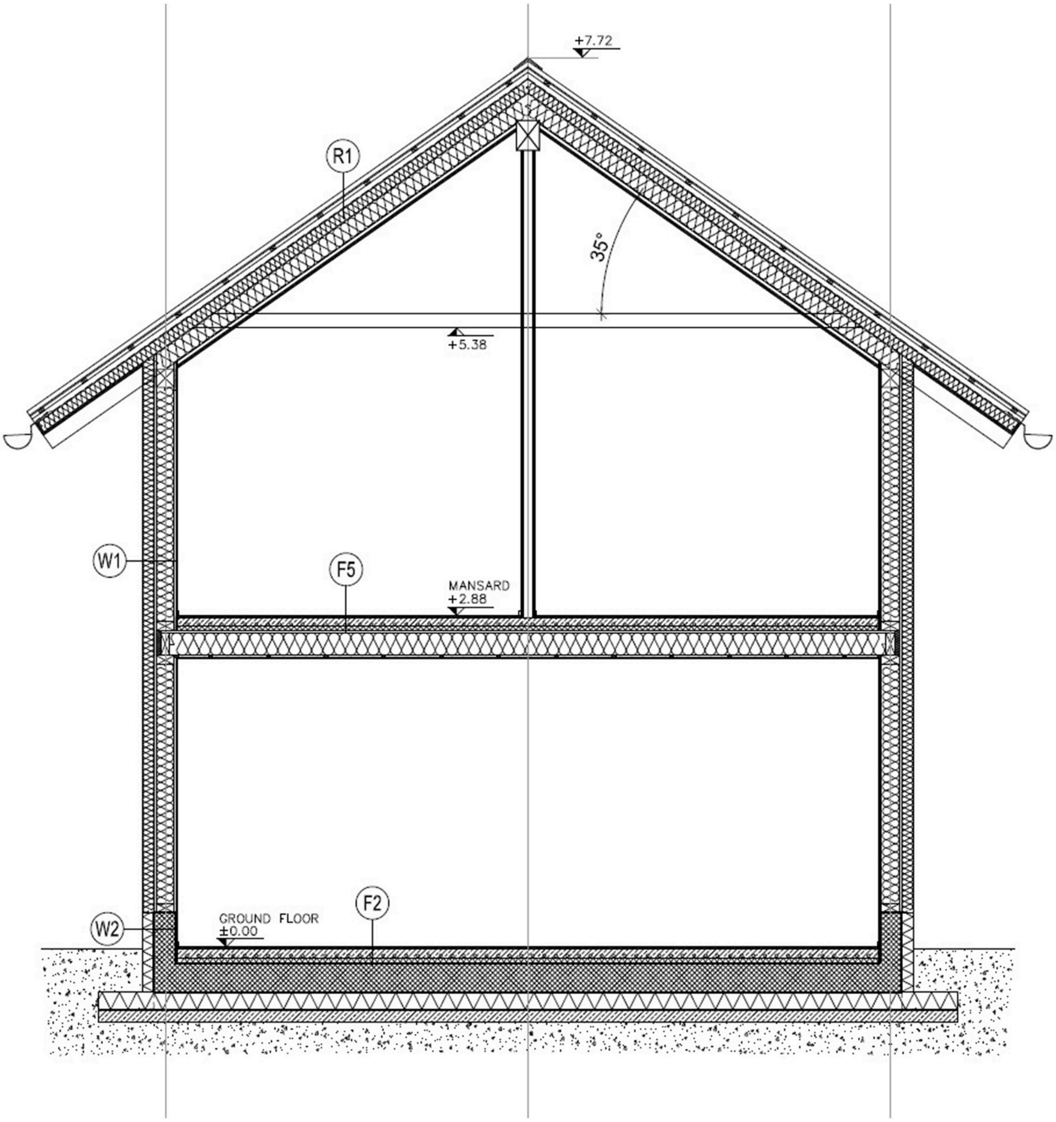

Fig. A7.

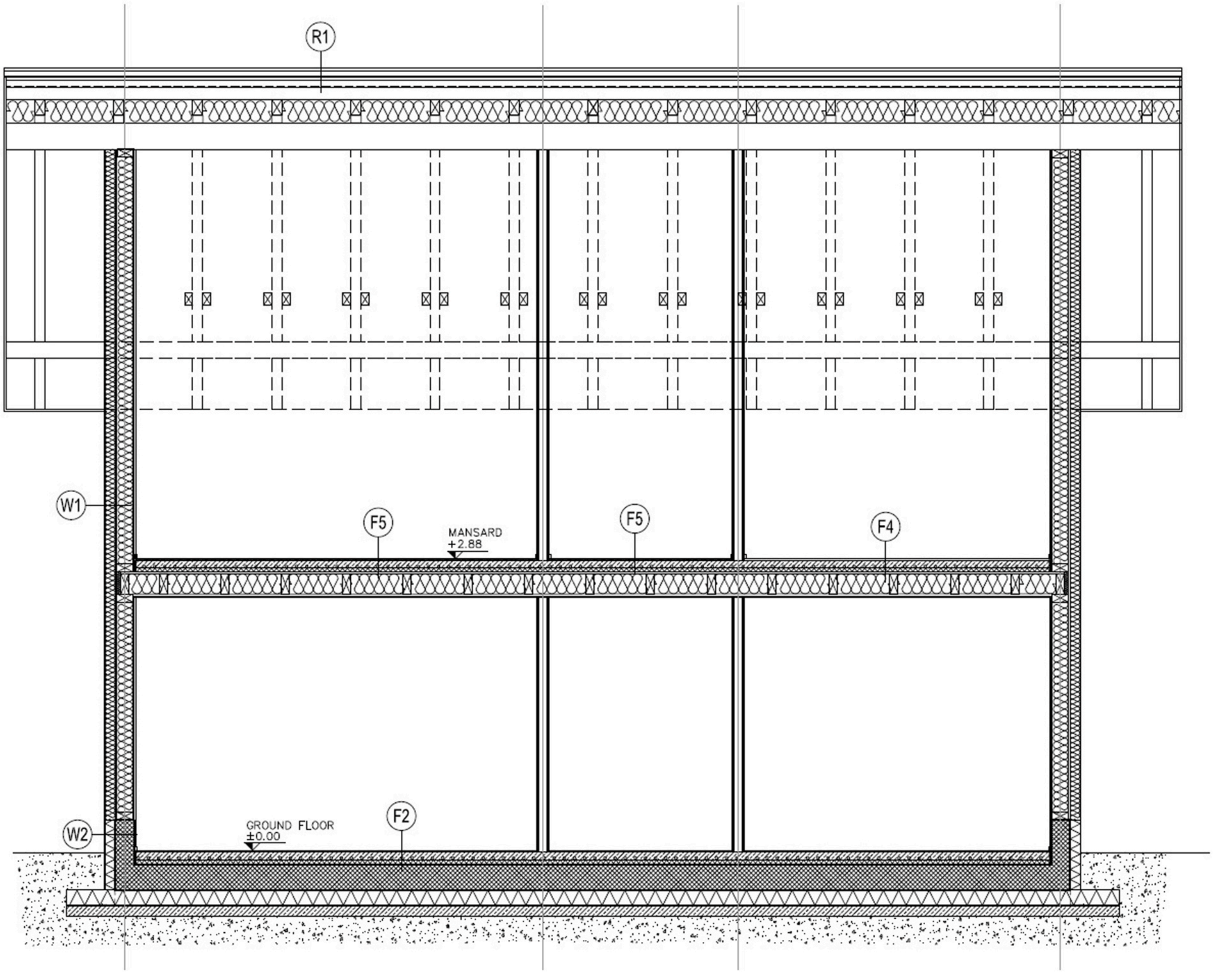

Fig. A8.

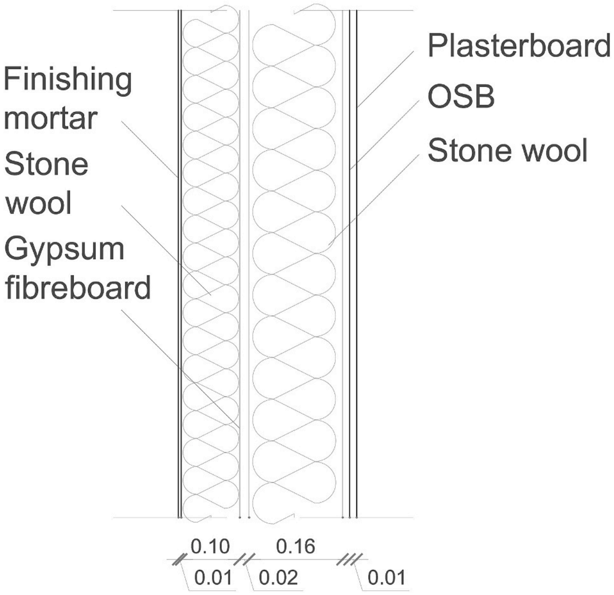

Fig. A9.

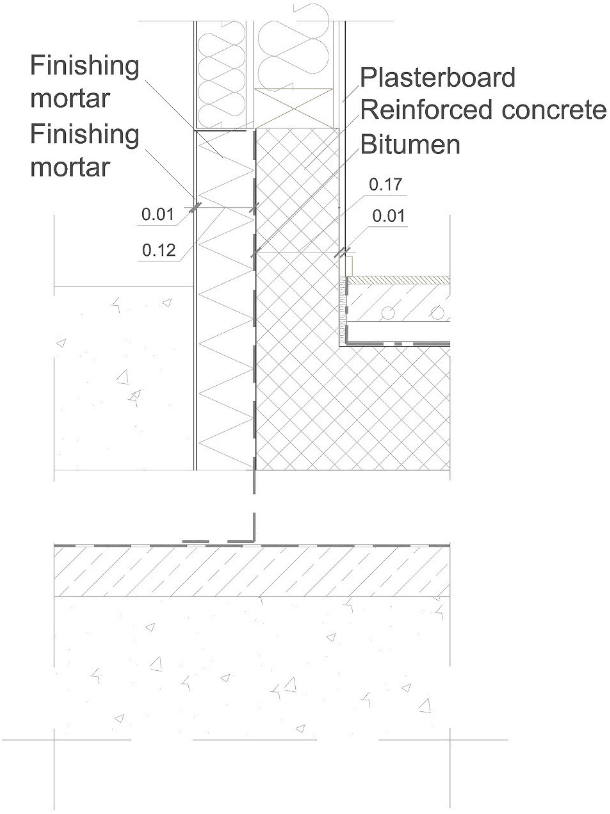

Fig. A10.

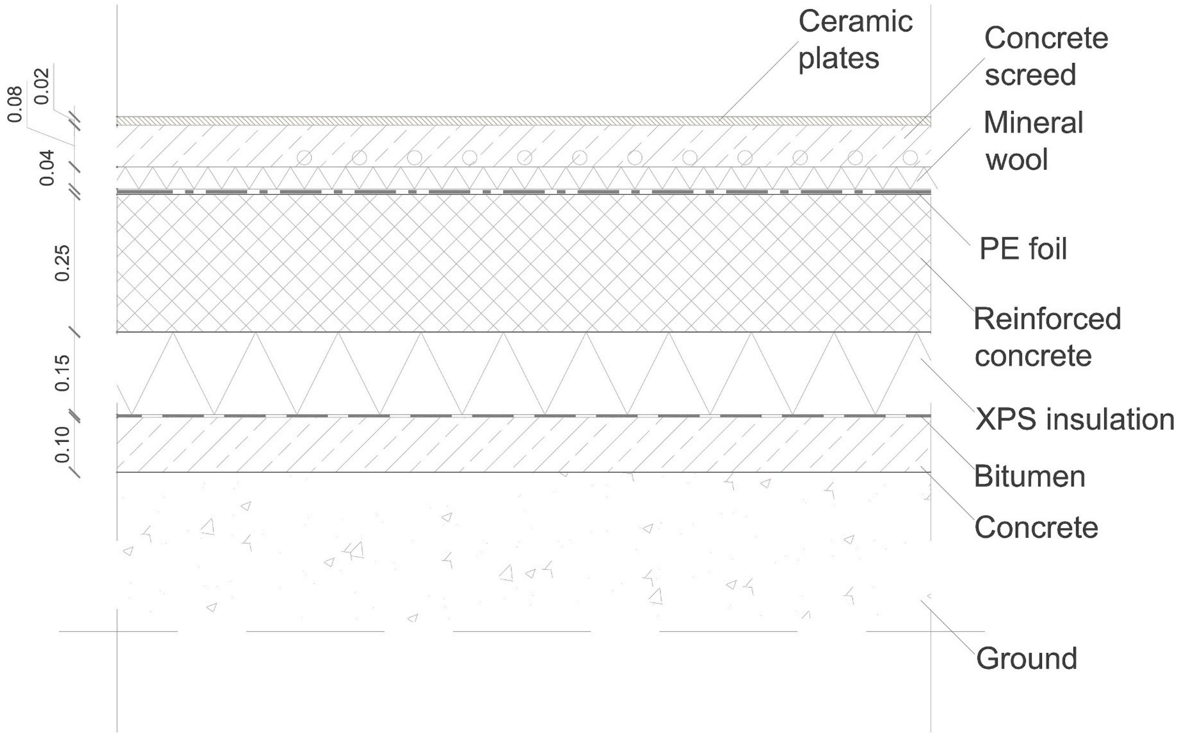

Fig. A11.

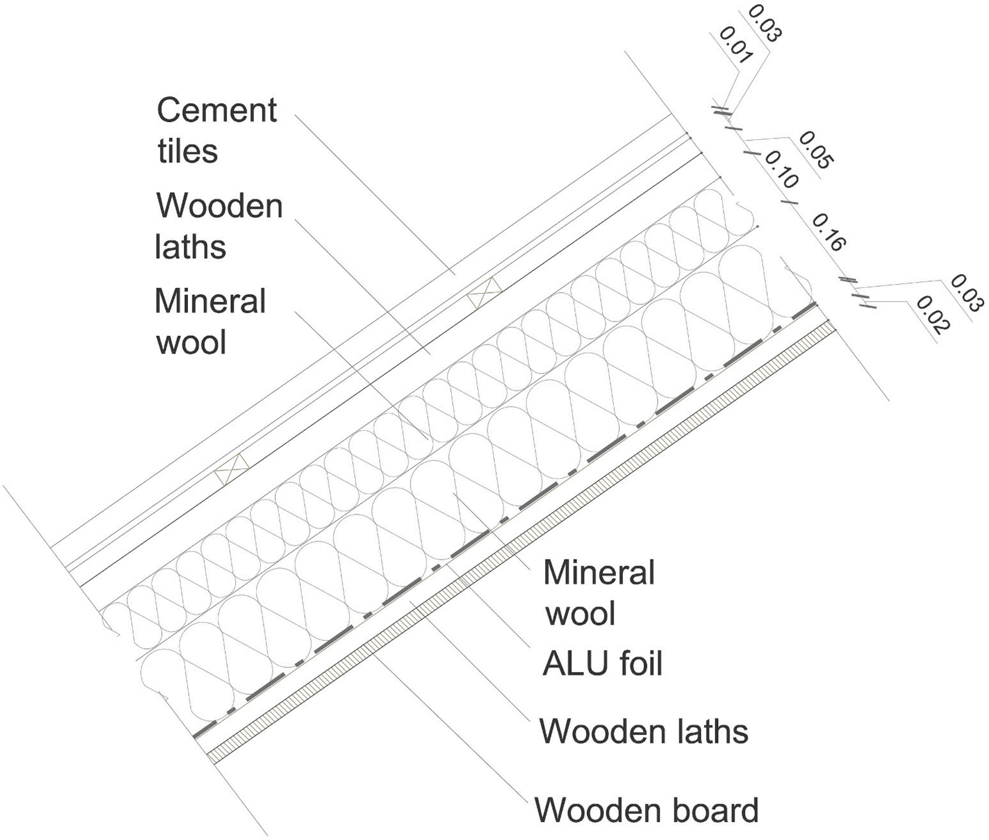

Fig. A12.

Table A1
W1. Exterior walls U = 0,146 W/m^{2}K

Material	thickness (cm)
Gypsum plasterboard	1.25
OSB plate	1.2
Stone wool between the load bearing construction profiles	16
Gypsum fiberboard	1.5
Stone wool	10
Reinforcing mortar, mesh and finishing plaster	0.6

Table A2
W2. Exterior wall ground floor bottom U = 0,262 W/m^{2}K

Material	thickness (cm)
Gypsum plasterboard	1.25
Reinforced concrete	16
Hydro isolation: polymer-bitumen	0.4
XPS insulation	12
Reinforcing mortar, mesh and finishing plaster	0.6

Table A3
W3 inner walls

Material	thickness (cm)
2 x Gypsum plasterboard	2 × 1.25
Mineral wool	7.5
2 x Gypsum plasterboard	2 × 1.25

Table A4
R1 roof U = 0,132 W/m^{2}K

Material	thickness (cm)
wooden boards	2
wooden laths	3
Reinforced ALU foil	0.2
Mineral wool between the load bearing construction profiles	16
Mineral wool between the load bearing construction profiles	10
Wooden laths	5
wooden laths in opposite direction	3
Cement roof tiles	0.5

Table A5
F1 ground floor-ceramics U = 0,175 W/m^{2}K

Material	thickness (cm)
Ceramic plates	1
Glue for ceramic plates	0.5
Concrete screed	7.6
PE foil	0.02
Mineral wool	4
Reinforced concrete	25
XPS insulation	15
Hydro isolation: bitumen	0.4
bottom concrete	10

Table A6
F1/A ground floor-ceramics in bathrooms U = 0,186 W/m^{2}K

Material	thickness (cm)
Ceramic plates	1
Glue for ceramic plates	0.5
Concrete screed	7.6
PE foil	0.02
Mineral wool	3
Reinforced concrete	25
XPS insulation	15
Hydro isolation: bitumen	0.4

Table A7
F2 ground floor parquet U = 0,174 W/m^{2}K

Material	thickness (cm)
Parquet	1.1
Glue	0.3
Concrete screed	7.6
PE foil	0.02
Mineral wool	4
Reinforced concrete	25
XPS insulation	15
Hydro isolation: bitumen	0.4
bottom concrete	10

Table A8
F4 1st floor ceramics

Material	thickness (cm)
Ceramic plates	1
Glue for ceramic plates	0.5
Concrete screed	7.6
PE foil	0.02
Mineral wool	3
OSB plates	1.5
stone wool between the load bearing construction profiles	20
wooden laths	2
Gypsum plasterboard	1.25

Table A9
F4 1st floor parquet

Material	thickness (cm)
Parquet	1.1
Glue	0.3
Concrete screed	7.6
PE foil	0.02
Mineral wool	4
OSB plates	1.5
stone wool between the load bearing construction profiles	20
wooden laths	2
Gypsum plasterboard	1.25

CRediT authorship contribution statement

Alberto Quintana-Gallardo: Conceptualization, Writing – original draft, Life Cycle Assessment, Building simulation. **Erwin M. Schau:** Conceptualization, Supervision, Writing – review & editing. **Eva Prelovšek Niemelä:** Conceptualization, Supervision, Writing – review & editing. **Michael D. Burnard:** Visualization, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Abd Rashid, A., Idris, J., Yusoff, S., 2017. Environmental impact analysis on residential building in Malaysia using life cycle assessment. Sustainability 9, 329. https://doi.org/10.3390/su9030329.

Aksamija, A., 2016. Regenerative design and adaptive reuse of existing commercial buildings for net-zero energy use. Sustain. Cities Soc. 27, 185–195. https://doi.org/10.1016/j.scs.2016.06.026.

American Society of Heating, Refrigerating and Air-Conditioning (ASHRAE), 2017 [WWW Document], URL. https://www.ashrae.org/.

Asdrubali, F., Baldassarri, C., Fthenakis, V., 2013. Life cycle analysis in the construction sector: guiding the optimization of conventional Italian buildings. Energy Build. 64, 73–89. https://doi.org/10.1016/j.enbuild.2013.04.018.

Attia, S., 2016. Towards regenerative and positive impact architecture: a comparison of two net zero energy buildings. Sustain. Cities Soc. 26, 393–406. https://doi.org/10.1016/j.scs.2016.04.017.

Bahramian, M., Yetilmezsoy, K., 2020. Life cycle assessment of the building industry: an overview of two decades of research (1995–2018). Energy Build. https://doi.org/10.1016/j.enbuild.2020.109917.

Baldassarri, C., Allacker, K., Reale, F., Castellani, V., Sala, S., 2017. Consumer Footprint: Basket of Products Indicator on Housing. https://doi.org/10.2760/05316.

Bastin, J.-F., Clark, E., Elliott, T., Hart, S., van den Hoogen, J., Hordijk, I., Ma, H., Majumder, S., Manoli, G., Maschler, J., Mo, L., Routh, D., Yu, K., Zohner, C.M., Crowther, T.W., 2019. Understanding climate change from a global analysis of city analogues. PLoS One 14. https://doi.org/10.1371/journal.pone.0217592.

Bellos, E., Tzivanidis, C., 2017. Energetic and financial sustainability of solar assisted heat pump heating systems in Europe. Sustain. Cities Soc. 33, 70–84. https://doi.org/10.1016/j.scs.2017.05.020.

Benachio, G.L.F., Freitas, M., do, C.D., Tavares, S.F., 2020. Circular economy in the construction industry: a systematic literature review. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2020.121046.

Climate Centre, 2018. UN: sahel region one of the most vulnerable to climate change [WWW Document]. URL. https://www.climatecentre.org/news/1066/un-sahel-region-one-of-the-most-vulnerable-to-climate-change.

Concerted action EPBD, 2020. Database - Energy Performance of Buildings Directive [WWW Document]. URL. https://epbd-ca.eu/database-of-outputs.

COST Action RESTORE, 2018. Working Group One Report: Restorative Sustainability.

Design Builder, 2019. DesignBuilder software Ltd [WWW Document]. URL. https://designbuilder.co.uk//.

Dias, W.P.S., Pooliyadda, S.P., 2004. Quality based energy contents and carbon coefficients for building materials: a systems approach. Energy 29, 561–580. https://doi.org/10.1016/J.ENERGY.2003.10.001.

Du Plessis, C., 2012. Towards a regenerative paradigm for the built environment. Build. Res. Inf. 40, 7–22. https://doi.org/10.1080/09613218.2012.628548.

Eberhardt, L.C.M., Birgisdóttir, H., Birkved, M., 2019. Life cycle assessment of a Danish office building designed for disassembly. Build. Res. Inf. 47, 666–680. https://doi.org/10.1080/09613218.2018.1517458.

European Commission, 2019. The European Green Deal.

European Commission, 2013. Recommendation 2013/179/EU on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations. Off. J. Eur. Union.

European Committee for Standardization, 2020. UNE EN 15804:2012+A2:2020 Sustainability of Construction Works - Environmental Product Declarations - Core Rules for the Product Category of Construction Products - European Standards.

European Environment Agency, 2020. Greenhouse Gas Emission Intensity of Electricity Generation [WWW Document]. URL. https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-6#tab-googlechartid_googlechartid_chart_111_filters=%7B%22rowFilters%22%3A%7B%7D%3B%22columnFilters%22%3A%7B%22pre_config_date%22%3A%5B2018%5D%7D%3B%22sortFilter%22%3A%5B%22index_2018%22.

European Statistical Office, 2020. Energy Consumption in Households - Statistics Explained [WWW Document]. URL. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_consumption_in_households#Energy_consumption_in_households_by_type_of_end-use.

Eurostat, 2019. Electricity generation statistics – first results - statistics explained [WWW Document]. URL. https://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_generation_statistics_–_first_results.

Guardigli, L., Monari, F., Bragadin, M.A., 2011. Assessing environmental impact of green buildings through LCA methods:A comparison between reinforced concrete and wood structures in the European context. In: Procedia Engineering. Elsevier Ltd, pp. 1199–1206. https://doi.org/10.1016/j.proeng.2011.11.2131.

Gustavsson, L., Joelsson, A., Sathre, R., 2010. Life cycle primary energy use and carbon emission of an eight-storey wood-framed apartment building. Energy Build. 42, 230–242. https://doi.org/10.1016/j.enbuild.2009.08.018.

Hafner, A., Ott, S., Winter, S., 2014. Recycling and end-of-life scenarios for timber structures. RILEM Bookseries 9, 89–98. https://doi.org/10.1007/978-94-007-7811-5_8.

Heating & Cooling Degree Days - Worldwide Data Calculation [WWW Document], URL. https://www.degreedays.net/. accessed 3.11.2021.

Hossain, Y., Marsik, T., 2018. Life cycle inventory data for life cycle assessment (LCA) of highly energy efficient case study house in Dillingham. Alaska 1. https://doi.org/10.17632/SG59VBRYX2.1.

International Energy Agency, 2021. World Energy Balances. Analysis.

IPCC - Intergovernmental Panel on Climate Change, 2020 [WWW Document], URL. http://www.ipcc.ch/.

ISO 14040, 2006. Environmental Management. Life Cycle Assessment. Principles and Framework.

Jayalath, A., Navaratnam, S., Ngo, T., Mendis, P., Hewson, N., Aye, L., 2020. Life cycle performance of cross laminated timber mid-rise residential buildings in Australia. Energy Build. 223, 110091 https://doi.org/10.1016/j.enbuild.2020.110091.

Lavagna, M., Baldassarri, C., Campioli, A., Giorgi, S., Dalla Valle, A., Castellani, V., Sala, S., 2018. Benchmarks for environmental impact of housing in Europe: definition of archetypes and LCA of the residential building stock. Build. Environ. 145, 260–275. https://doi.org/10.1016/j.buildenv.2018.09.008.

Lützkendorf, T., 2018. Assessing the environmental performance of buildings: trends, lessons and tensions. Build. Res. Inf. 46, 594–614. https://doi.org/10.1080/09613218.2017.1356126.

Mang, P., Reed, B., 2012. Designing from place: a regenerative framework and methodology. Build. Res. Inf. 40, 23–38. https://doi.org/10.1080/09613218.2012.621341.

Marsh, R., 2017. Building lifespan: effect on the environmental impact of building components in a Danish perspective. Architect. Eng. Des. Manag. 13, 80–100. https://doi.org/10.1080/17452007.2016.1205471.

Natanian, J., Auer, T., 2020. Beyond nearly zero energy urban design: a holistic microclimatic energy and environmental quality evaluation workflow. Sustain. Cities Soc. 56, 102094 https://doi.org/10.1016/j.scs.2020.102094.

Odyssee-Mure, 2020. Sectoral Profile - Households.

Ripple, W.J., Wolf, C., Newsome, T.M., Barnard, P., Moomaw, W.R., 2020. World scientists' warning of a climate emergency. Bioscience. https://doi.org/10.1093/biosci/biz088.

Röck, M., Hollberg, A., Habert, G., Passer, A., 2018. LCA and BIM: Visualization of environmental potentials in building construction at early design stages. Build. Environ. 140, 153–161. https://doi.org/10.1016/j.buildenv.2018.05.006.

Sala, S., Cerutti, A.K., Pant, R., 2018. Development of a Weighting Approach for the Environmental Footprint. Publications office of the European Union.

Schau, E.M., Prelovšek Niemelä, E., Niemelä, A.J., Alencar Gavric, T.A., Šušteršič, Iztok, 2019. Life cycle assessment benchmark for wooden buildings in Europe: single family house - nearly zero-energy building (nZEB). In: The 9th International Conference on Life Cycle Management (LCM2019). Poznan 1-4 Sep.

Schnieders, J., Feist, W., Rongen, L., 2015. Passive houses for different climate zones. Energy Build. 105, 71–87. https://doi.org/10.1016/j.enbuild.2015.07.032.

Slorach, P.C., Stamford, L., 2021. Net zero in the heating sector: technological options and environmental sustainability from now to 2050. Energy Convers. Manag. 230, 113838 https://doi.org/10.1016/j.enconman.2021.113838.

U.S. Energy information administration, 2019. Global energy consumption driven by more electricity in residential, commercial buildings - today in energy [WWW Document]. URL. https://www.eia.gov/todayinenergy/detail.php?id=41753#.

UNEP, ISWA, 2015. Global Waste Management Outlook. Vienna, Austria.

United States Department of Energy, 2019. EnergyPlus [WWW Document]. URL. https://www.energy.gov/eere/buildings/downloads/energyplus-0.

Weather Spark, 2021 [WWW Document], URL. https://weatherspark.com/.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8.

Wilson, D.C., 2007. Development drivers for waste management. Waste Manag. Res. J. a Sustain. Circ. Econ. 25 https://doi.org/10.1177/0734242X07079149.

Yong, S.G., Kim, J.H., Gim, Y., Kim, J., Cho, J., Hong, H., Baik, Y.J., Koo, J., 2017. Impacts of building envelope design factors upon energy loads and their optimization in US standard climate zones using experimental design. Energy Build. 141, 1–15. https://doi.org/10.1016/j.enbuild.2017.02.032.

Zampori, L., Pant, R., 2019. Suggestions for Updating the Product Environmental Footprint (PEF) Method, JRC Technical Reports. https://doi.org/10.2760/424613.

[WWW Document] Zebra 2020. Energy Efficiency Trends in Buildings, 2020. URL. https://zebra-monitoring.enerdata.net/overall-building-activities/share-of-new-dwellings-in-residential-stock.html.

Zhang, X., Skitmore, M., De Jong, M., Huisingh, D., Gray, M., 2015. Regenerative sustainability for the built environment - from vision to reality: an introductory chapter. J. Clean. Prod. 109, 1–10. https://doi.org/10.1016/j.jclepro.2015.10.001.