Environmental impacts of 3D-printed and conventional houses and applicability of 3D-printing to provide sustainable housing in developing countries

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Contents

Abstract

Construction is one of the most polluting industry sectors (Ametepey et al., 2015). Given the population and urbanisation growth that is expected in the coming years and the subsequent necessity for housing, it is important to implement ways to reduce the environmental impacts of construction. Additive manufacturing, the process of creating an object by building it one layer at a time, was found to be a viable option, but since it is still a relatively new technology, there is a lack of research assessing its sustainability. Moreover, it is also important to determine the social sustainability and the impacts that it might have on the labour market. The present research therefore focused on calculating and comparing the environmental impacts of 3D-printing versus conventionally built houses. The potential and limitations of using 3D-printing to provide housing in developing countries was also investigated. A Life Cycle Assessment on four 3D-printed and ten most conventionally built houses was performed. 3D-printed buildings were found to perform better than conventional ones in all the environmental impact categories considered. Three experts were interviewed to determine the potential of 3D-printing of providing sustainable housing in developing countries. Printing material availability, legal gaps, cultural resistance, and uncertainty in how the labour market would respond to 3D-printing are the main limitations highlighted during the interviews. To overcome these challenges, investments in the sector could be increased, and new norms implemented to guarantee the safety of the 3D-printed buildings.

Introduction

Background

In 2015, the United Nations General Assembly adopted the 2030 Agenda for Sustainable Development, a shared blueprint for peace and prosperity for people and the planet. The trajectory is guided by 17 Sustainable Development Goals (SDGs), which are described as “an urgent call for action by all countries - developed and developing - in a global partnership”. The SDGs concern the main challenges that need to be addressed to achieve a just and sustainable future for all, including poverty, health, environmental issues, climate change, gender inequality, education, and many more (United Nations, 2015).

SDG 11.1 plays a crucial role as a social determinant of health and wellbeing (Rolfe et al., 2020), and improved housing can prevent disease, increase the quality of life, reduce poverty, and help mitigate climate change (World Health Organization, 2018). SDG 11 aims at making cities and human settlements inclusive, safe, resilient, and sustainable by 2030 (United Nations, 2022). Nevertheless, 150 million people globally are homeless (Homeless World Cup Foundation, 2020), and more than 1 billion live in slums or informal settlements, with 370 million in Eastern and South-Eastern Asia, 238 million in sub-Saharan Africa, and 227 million in Central and Southern Asia (UN. Secretary-General, 2021). Moreover, population is growing and 60% of the global population is expected to reside in cities by 2030. This means that 3 billion people will require adequate and affordable housing (UN. Secretary-General, 2021).

Building houses however comes with an environmental cost. It has been estimated that globally, 35% of final energy use and 39% of the energy and process-related CO_2 emissions in 2018 came from the building and construction sector (IEA, 2019). In the United States, construction is the third largest sector in terms of emissions of greenhouse gasses (GHG) (Truitt, 2009). Identifying how each life phase of the buildings contributes to the final emissions is an important step for finding ways of reducing them. It has been determined that 27% of the emissions come from building operations, while 20% depend on building materials and construction (United Nations Environment Programme, 2021). In the UK, the manufacturing and transport of building materials alone accounts for 8% of all primary energy use (Morel et al., 2001).

Along with the emission of GHG and the consequent contribution to global warming, construction activities are responsible for more environmental impacts. Ametepey et al. (2015) surveyed 100 construction practitioners regarding the most relevant environmental aspects affected by construction. The results showed that resource consumption was the most relevant impact. The construction sector is one of the largest exploiters of natural resources: building construction consumes 40% of the world's raw stones, gravel, and sand, 25% of the virgin wood, and 16% of water per year (Ametepey et al., 2015). The extraction of raw materials causes degradation of the landscape and introduction of pollutants into the atmosphere and the biosphere (Ametepey et al., 2015). The effect on biodiversity was indicated as the second most relevant environmental impact from construction, followed by local issues, such as noise pollution and vibration, transport issues, waste generation, atmospheric emissions of volatile organic compounds (VOCs) and chlorofluorocarbons (CFCs), accidents and incidents, soil alteration, and water emissions.

Since the construction phase accounts for a large quota of the building life cycle emissions, finding alternative construction methods and materials is an important step to mitigate the environmental impacts of edifices. A possibility is to source sustainable and locally available materials to cut-out the transportations emissions and reduce the impact of the materialization stage (Li et al., 2021). For instance, replacing typical conventional houses in the Philippines with cement–bamboo frames, coconut board-based houses and soil–cement blocks reduced the emissions of CO_2-eq by respectively 4.4, 9.3, and 10.3 t over a 25 years span (Salzer et al., 2017). Using low carbon emissions materials such as straw-bale, wood frame glass windows, and resin tiles can reduce the GHG emissions by 39.5% compared to conventional materials (Li et al., 2021). Another strategy to reduce the emissions is to prefabricate the buildings or some components and then transporting semi-assembled parts to the building site, as opposed to *in situ* construction. This technique is widely used in Japan, where 25-28% of homes are industrially produced, while China aims at prefabricating 30% of all the new buildings to be constructed over the next 30 years (Du et al., 2019). Prefabricated building produce approximately 18% less CO_2 emissions compared to conventional ones (Du et al., 2019).

Another promising technology is additive manufacturing, or 3-dimensional printing (3D printing). It consists of creating physical objects from a geometrical representation by successive addition of materials (Shahrubudin et al., 2019). This technology has been developed in the 1980s and its adoption is increasing across different sectors, such as healthcare (Liaw et al., 2017), food processing (Nachal et al., 2019), automotive (Ramya et al., 2016), aerospace (Tay et al., 2017), and fashion (Vanderploeg et al., 2017). The construction sector is well-suited for the utilisation of 3D-printing. Firstly, labour requirements can be reduced, decreasing the cost and time of a project, and increasing site safety (Holt et al., 2019). Also, additive manufacturing removes design limitations typical of conventional construction methods. Curvilinear forms are stronger than linear ones, yet they are harder to build; with 3D-printing, this limitation is overcome as curvilinear designs can be executed as easily as angular ones (Holt et al., 2019). There are many additive manufacturing techniques and the ones typically used in construction are based on the extrusion of a concrete-mix through a nozzle (El-Sayegh et al., 2020). Currently available high-performance cement-based materials cannot always be 3D-printed because they do not always meet the printability and solidification requirements: the mix needs to be liquid enough to pass through the nozzle, it needs to solidify fast enough to allow for a layer-by-layer deposition, and it needs to be strong enough to support the weight of the upper layers without cracking (De Schutter et al., 2018). Many 3D-printing companies sell proprietary concrete-mixes to be used with their printers (Black Buffalo, etc.), while others allow to use some market available ones as well (COBOD). Some companies do not use concrete at all, replacing it by locally available and more eco-friendly materials such as clay (WASP).

Not all the parts of a building can be 3D-printed. Foundations and outer and inner walls are typically 3D-printed, while closing the house with roof, doors and windows is completed with conventional techniques. Finishings such as paint, floors, electricity, heating, ventilation, and air conditioning (HVAC) are also integrated in the same way as for conventional buildings (COBOD, 2022).

3D-printing is advertised by the companies that provide it as a sustainable, cost- and time-effective, safe, and reliable way of building houses. This claim though is often not supported by publicly available data and makes it hard for researchers to assess the actual environmental performance of the technology (Oberti et al., 2015). Some studies determine the environmental impacts of 3D-printed houses, but the analyses are often limited to a single case study or a comparison between a 3D-printed house and a conventionally built one. There is a lack of comprehensive analyses that compare the environmental impacts of several case studies. Moreover, if 3D-printing fulfils the promise of being a cheaper, faster, and more sustainable alternative to conventional construction, it could be a promising solution to provide housing in developing countries.

Research questions

Two main research objectives are identified. Firstly, the study aims at determining the climate impacts of 3D-printing houses compared to conventionally building them. Several environmental impacts will be assessed, such as contribution to global warming, land use, marine and freshwater eutrophication, ecotoxicity, human toxicity, water and resources consumption and more. For each of the considered impacts, the contribution of every building material to the overall effect will be estimated. Furthermore, it will be observed how emissions change by choosing different compositions of the main building materials. To answer these questions, a quantitative research approach will be used. Data on the type and amount of the building materials used to 3D-print or conventionally build houses will be collected and then analysed.

The second research goal is to understand the applicability of 3D-printing to provide sustainable housing solutions in developing countries. In particular, the main limitations and how to overcome them will be evaluated. A qualitative research approach consisting of structured or semi-structured interviews with experts will be used.

Outline of the thesis

The present thesis will be structured as follows: first, an introduction to the topic with relevant background information is provided, followed by the research questions. Next, in the literature and conceptual framework, the existing literature concerning the research questions is discussed. In the same section, the tools and methods currently available to answer the research questions are evaluated. Later, in the methodology part, the methods are discussed in detail: the general research approach is presented, followed by an explanation of how data were collected and treated. Here, research quality aspects such as how reliability and validity are pursued is illustrated. Subsequently, in the results section, the findings are presented and later discussed. The thesis ends with the conclusions and recommendations for future development.

Literature and conceptual framework

The first research objective aims at determining and comparing the environmental impacts of 3D-printed and conventionally built houses. The main methodology chosen to investigate the environmental impacts of 3D-printed buildings is Life Cycle Assessment (LCA). LCA is an internationally standardised methodology that allows to determine the environmental burden of products, processes, or systems throughout their entire life cycle, form raw materials extraction to final disposal. Some of the advantages of LCA are that it is a comprehensive assessment method and that it highlights potential environmental trade-offs (Curran, 2014). The main disadvantage is that, even if it is an ISO standardised methodology, a lot is left to the interpretation to the researcher, and it has been shown that different LCAs performed on the same product can provide very different results (Curran, 2014). In spite of its limitations, it has been consistently used to assess the environmental impacts of buildings since 1990 because of its integrated way of treating the framework (Khasreen et al., 2009).

Previous studies showed that 3D-printed houses tend to perform better in terms of environmental impacts than conventional buildings. A study by Alhumayani et al. (2020) used LCA to assess the environmental impacts of 3D-printed and conventional concrete. The results showed that 3D-printed concrete (3DPC) performed around 50% better in all the environmental impact categories that were considered. It also found that most of the impacts of conventional concrete came from the use of steel bars, while the impacts of 3DPC depended on the mix of materials used. This shows the potential of adjusting the formulations to ulteriorly reduce the impacts on the environment. Another study by Mohammad et al. (2020) compared the impacts of conventional construction and three 3DPC alternatives, namely with steel reinforcement, without any reinforcement, and without reinforcement and using lightweight printable concrete. They performed a LCA and chose 1m^2 of wall as a functional unit. The results confirmed the advantages of 3DPC over conventional construction and pointed out the importance of finding new reinforcement techniques suitable for 3D-printing. A further study performed an LCA to compare the cradle-to-grave environmental impacts of a 3D-printed and a conventionally built house. The findings highlighted that the conventional building performed worse in all environmental impact categories; this is justified by the smaller need for building materials in 3D-printing than conventional houses (Ali, 2019).

To determine the applicability of 3D-printing to provide sustainable housing in developing countries, a qualitative research approach was chosen. Interviews are the most commonly used tool to collect data in qualitative research (Cassell, 2005). It is widely used because it allows to gather first-hand information from relevant sources, but it also comes with some limitations. One of the main ones is that the interviewer could accidentally cause biases, either related to the way the questions are asked, to the gender or ethnicity of the interviewer, to the reactions to the answers and so on (Alsaawi, 2014). Regarding the goal of the present study, some research was already conducted on the challenges around implementing 3D-printing for construction. A study on benefits, challenges, and risks of 3DPC pointed out that the main challenges concern finding the appropriate materials, creating and managing the software, understanding the new design and architectural principles that differ from conventional construction, overcoming the lack of codes and regulations, dealing with scepticism, and finally considerate how the labour market would respond to a large-scale use of the technology in construction (El-Sayegh et al., 2020). Since the construction sector is one of the major sources of employment in the world (Hossain et al., 2020), it is relevant to understand how it could adapt to the introduction of automation techniques such as additive manufacturing. A possibility is that countries will upskill the existing workers (Millington, 2017). Moreover, many developed countries are experiencing a shortage in the construction sector and rely on migrant workers to meet the demand (El-Sayegh et al., 2020).

Methodology

Given the interdisciplinarity of the research, both quantitative and qualitative research methods were used. To answer the research question concerning the environmental impacts of 3D-printed and conventionally built houses, a quantitative approach was used, while to answer the question regarding the applicability of 3D-printing to provide sustainable housing in developing countries, a qualitative research approach was preferred. The methodology section will therefore be divided into two parts.

Determining the environmental impacts of 3D-printed and conventionally built houses

Life Cycle Assessment

To determine the environmental impacts of 3D-printed and conventionally built constructions, life cycle assessment (LCA) analyses of 14 case studies were conducted. According to the 14000 series of environmental management standards of the International Organization for Standardization (ISO), LCA consists of four main stages, namely (1) Goal and Scope Definition, (2) Inventory Analysis, (3) Impact Assessment, and (4) Interpretation.

(1) Goal and Scope Definition
The goal of the LCA is to determine the environmental impacts of 3D-printed and conventionally built houses. 1 m^2 of the Gross Floor Area (GFA) was adopted as a functional

unit to carry out the comparison. The results can be of interest for 3D-printing companies to better understand their environmental performance and to know how to reduce the impacts from their building materials. Figure 1 shows the boundaries of the system, including production and manufacturing of materials, construction, operation, maintenance, and end of life phase. The LCA was limited to material extraction and construction phase, including the transport of materials to the site and energy consumption during the considered processes. All the elements that are the same in 3D-printed and conventional houses are considered out of scope (Figure 1). The construction elements included in the analysis are foundations and outer and inner walls.

(2) Data on the building materials used to 3D-print four houses and to conventionally build ten were collected. Information on the 3D-printed houses was obtained by contacting the 3D-printing companies involved in the construction projects. Many more companies were contacted but refused to share the data. Data regarding the other houses was retrieved from papers that shared the bills of materials used for the construction. Bills of materials (BOM are defined as “a comprehensive inventory of raw materials, assemblies, subassemblies, parts and components, as well as the quantities of each needed to manufacture a product” (Lutkevich et al., 2022). The list of materials was inserted in SimaPro ("About SimaPro," 2022) using the Ecoinvent 3 Database with allocation at point of substitution (APOS). The Ecoinvent Database is a Life Cycle Inventory (LCI) database that enables users to understand the environmental impacts of different products and services; it contains more than 18’000 datasets regarding human activities or processes ("ecoinvent Database," 2022). The Unit processes were preferred to system ones. Such data include foreground components such as quantity of materials, transportation, and energy consumption. Table 1 and 2 give an overview of the material used per functional unit (FU=1m^2).

(3) The data were analysed in Simapro using the ReCiPe 2016 v1.1 midpoint (H) and ReCiPe 2016 v1.1 endpoint (H) indicators (Huijbregts et al., 2017). The endpoint indicators are used to show the damage to 3 areas of protection, namely human health, ecosystems, and resource availability. The midpoint indicators are defined somewhere between the emission and the endpoint, and are climate change, stratospheric ozone depletion, ionizing radiation, ozone formation (human health), fine particulate matter formation, ozone formation (terrestrial ecosystems), terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, land use, mineral resource scarcity, fossil resource scarcity, and water consumption.

(4) Once all the data were collected and analysed, the impacts of 3D-printed and conventionally built houses were compared. T-tests were performed to assess whether the mean of the two types of buildings deviated significantly for each impact category. Finally, SimaPro was used to assess the contribution of each building material to the total emissions from each case study. Lastly, a sensitivity analysis was carried out by determining how the environmental impacts change by changing the materials that contribute the most.

Description of the case studies

Conventional buildings

Germany 1

It is a synthetic building; it is an aggregate structure derived from various representative buildings with similar characteristics. This case is a typical one/two family house built in Germany according to the standards of the years 1991-2010. It has a Gross Floor Area (GFA) of 257 m^2 (Leibniz Institute of Ecological Urban and Regional Development et al., 2022).

Germany 2

It is also a synthetic building. It represents a multifamily house built in Germany between 1991 and 2010. It is typically composed of two or four floors and the GFA is 880 m^2 (Leibniz Institute of Ecological Urban and Regional Development et al., 2022).

Canada 1

The building is two-story dwelling house located in Vancouver. It was constructed in 1980 and has a GFA of 236.15 m^2 (Zhang et al., 2014).

Canada 2

It is a 8 story building located in Vancouver. The GFA is 4160m^2, and the height is 26.4m. The load bearing structure is composed by concrete columns and beams, (Venkatesh et al., 2015).

New Jersey

The building is located in Monmouth County, New Jersey and has a GFA of 317 m^2. It was built following the LEED-H (Leadership in Energy and Environmental Design - House) standards. A light frame wood construction with concrete block walls was used for the structure, while wood studs was used for the interior and exterior walls (Mosteiro-Romeroa et al., 2014).

Switzerland

This is a four-bedroom two-story single-family house in Chur, Switzerland and it is a Minergie-P certified building design. The GFA is 353 m^2 and the structure is made of light frame wood construction with reinforced concrete exterior and brick interior walls (Mosteiro-Romeroa et al., 2014).

Spain

The house is a typical Mediterranian home located in Barcelona. The GFA is 160 m^2 and the building is two-storeys high and mainly made of brick. (Ortiz-Rodríguez et al., 2010).

Colombia

This is a 140 m ^{2} house situated in Colombia, in the city of Pamplona. It is part of an existing semidetached house divided into two storeys. The main building materials are brick, concrete, and steel (Ortiz-Rodríguez et al., 2010).

Cameroon 1

This house was built in Cameroon using mainly concrete blocks. The building is a one storey home and has a GFA of 95.4 m^2 (Abanda et al., 2014).

Cameroon 2

The building is composed of mud-bricks and is located in Cameroon. Mud-bricks are air-dried briks made of loam, mus, sand and water mixed with a binder. The house is a one storey building with a GFA of 68.7 m^2 (Abanda et al., 2014)

Black Buffalo

This case study is a house that was 3D-printed at the NAHB International Builder's Show in Orlando, Florida. The house has a gross floor area of 31.12 m^2 and it was printed using the NEXCON^{TM} 3D printer and Black Buffalo Concrete Ink Mix.

Hous3Druck

Hous3Demo is a two storeies house printed in Beckum, Germany. The GFA is 160m^2, and it was printed using the BOD 2, a 3D printer built by the Danish company COBOD.

COBOD

The BOD was the first house to be 3D-printed in Europe. It was printed in Copenaghen, Denmark by the BOD 2 printer and it has a GFA of 50 m^2. To reduce the enviromental impacts, recycled roofing tiles were used in the printed mix along with mortar cement and sand and gravel as aggregates.

WASP

GAIA, the house printed by the Italian company WASP, represents the only case study in which concrete was not used. A mixture of soil taken from the surrounding landscape was used as printing material by the Crane-WASP technology. The end result is a 20 m^2 house in Massa Lombarda, Italy.

Determining the applicability of 3D-printing in developing countries

Experts from different backgrounds were contacted and asked to participate in an interview about the limitations of large-scale use of 3D-printing in construction in developing countries. Structured interviews were chosen as a method of investigation and the questions focused on the areas of expertise of the interviewee. Three semi-structured interviews to three different people were online. The first expert was Jadille Mussa Castellano. She is associate professor of Environmental Law at the Universidad Central in Santiago, Chile. Her work revolves around legal environmental issues related to housing and new technologies. She was asked to participate in the research because the legal gaps around 3D-printing are an important challenge to a large-scale use of 3D-printing in construction. The second interviewee was Carlos David Gonzales Cabrera. He is an architect and Professor of Architecture at the Universidad Pontificia Bolivariana de Medellín, in Colombia. The third interviewee was Jenee A. Jagoda, engineer and currently Engineering Flight Commander in the US Air Force. She was asked to participate because she previously worked on the viability of 3D-printed construction in remote environments. The interviews were online, and the answers collected and analysed by summarising and comparing the findings.

Table 1. Inventory of inputs per functional unit of conventional constructed buildings

	Germany 1	Germany 2	Canada 1	Canada 2	USA	Switzerland	Spain	Colombia	Cameroon 1	Cameroon 2
Concrete [kg]	283.62	899.19	136.46	3287.16	497.55	962.99	194.99	187.33	671.58	283.35
Cement [kg]	103.89	379.38	43.18	129.22	34.44	84.54	12.45	13.58	86.36	46.07
Aggregate [kg]	79.38	202.72	0.00	0.00	111.91	73.15	0.00	0.00	2.61	1.83
Brick [kg]	242.80	1289.10	22.36	0.00	0.00	51.35	87.74	71.98	0.00	197.91
Timber [kg]	6.23	17.90	20.06	441.36	21.17	23.15	2.18	10.70	0.91	0.00
Steel [kg]	14.79	98.44	7.31	34.24	3.23	21.71	3.62	5.72	0.00	0.00
Electricity [kg]	68.00*	68.00*	68.00*	68.00*	68.00*	68.00*	68.00*	68.00*	68.00*	68.00*

Table 2. Inventory of inputs per functional unit of conventional constructed buildings. The transportation of the 3D-printer and the weight are given as absolute values and not per functional unit.

	Black Buffalo	Hous3Druk	COBOD	WASP
Cement [kg]	218.19	334.31	122.40	0.00
Aggregate [kg]	416.00	622.12	227.60	56.25
Clay [kg]	0.00	0.00	0.00	131.25
Lime [kg]	0.00	0.00	0.00	75.00
Polypropylene fibres [kg]	1.28	2.19	0.40	0.00

Water [kg]	64.27	90.69	33.20	75.00
Electricity [kWh]	10.60*	10.60*	10.60*	10.60*
3D-printer transport [km]	250.00	534.00	0.80	0.00
3D-printer weight [kg]	19000.00	5390.00	5390.00	150.00

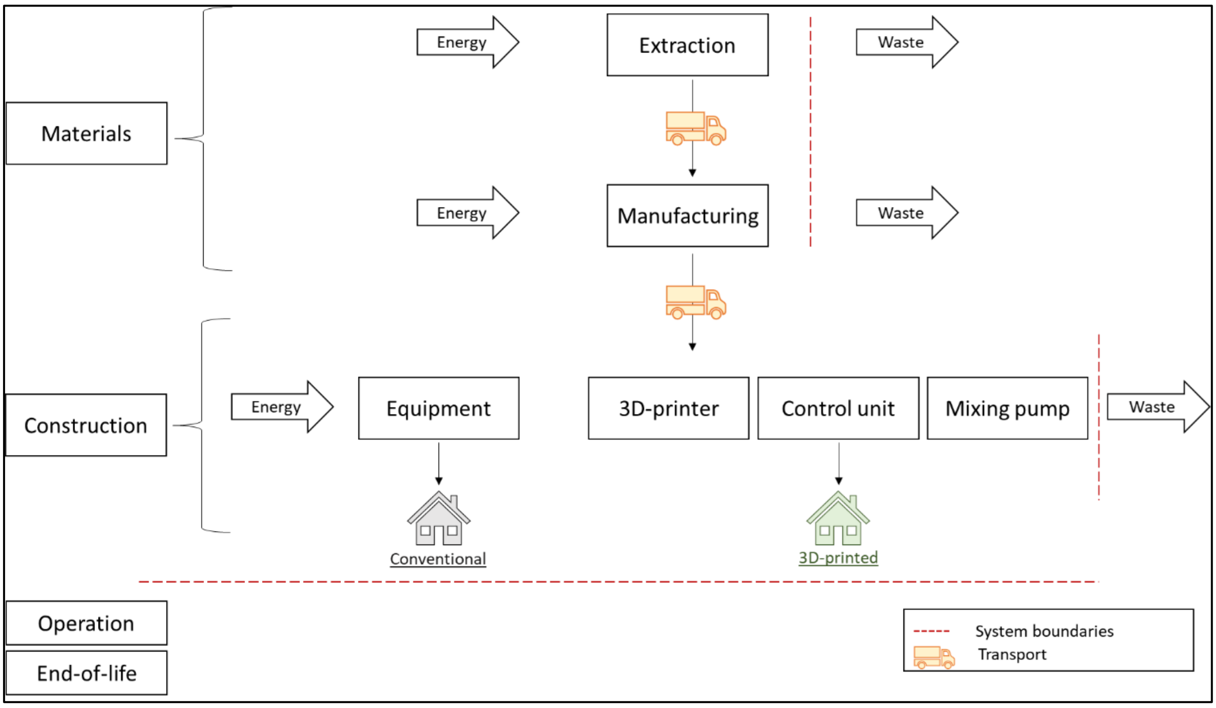


Figure 1. System boundaries of the LCA to determine the environmental impacts of 3D-printed and conventionally built houses.

Results

Environmental impacts of 3D-printed and conventionally constructed houses

Contribution to Climate Change

The contribution to climate change is expressed in terms of global warming potential (GWP), which quantifies the increase of the integrated infrared radiative forcing of a greenhouse gas (GHG) and is measured in kg of CO_2 equivalent (Huijbregts et al., 2017). The GHG emissions from the fourteen case studies were calculated and the results are presented in Figure 2. The average kg of CO_2 emitted per m^2 of conventional building was 173.32, and the value dropped to 69.08 for 3D-printed houses. All the conventional buildings showed greater emissions than the 3D-printed ones. Moreover, the emissions from the conventional buildings showed more variability than those from 3D-printed houses. The standard deviation (SD) was 78.04 for conventional buildings and 14.58 for 3d-printed ones.

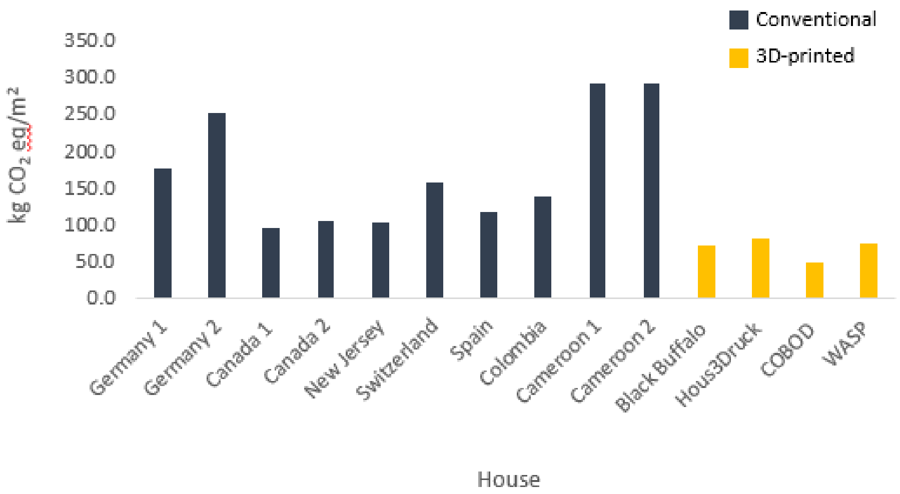


Figure 2. Contribution of conventional (black bars) and 3D-printed (yellow bars) houses to global warming, expressed as kg CO_2 eq/m^2.

The contribution of various building materials, energy use and the transportation of the 3D-printer to the construction site were assessed and the results are shown in Figure 3. The contribution of concrete and cement fluctuated between 25% (Colombia) and 90% (Cameroon cement) for conventional buildings. In 3D-printed houses, cement was the main component, and the contribution ranged between 57% (Black Buffalo) and 88% (COBOD). Bicks were not used for all the conventional houses but when they were, the contribution to emissions varied between 6% (Switzerland) and 38% (Africa 2), with an average contribution of 24%. 5% to 25% of the emissions of conventional houses came from steel, which is used as a reinforcement for concrete. In 3D-printed buildings, polypropylene fibres substituted steel and contributed between 2% to 6%, when used. The contribution of timber in conventional houses went from less than 1% to 17%. The contribution of aggregates, such as gravel and sand was always below 1% for conventional building and ranged between 2 and 4% in 3D-printed ones. Electricity was responsible for 9 to 28% of emissions from conventional houses and 5 to 9% from 3D-printed buildings. The transportation of the printer also contributed to the emissions and varied greatly based on the transportation distance: it accounted for 0.05% for COBOD, 7% for Hous3Druk, and 30% for Black Buffalo. WASP represents an exception because it was not printed with concrete, but with a mixture of clay and lime. 93% of the emissions came from lime, 2% from clay, and 5% from electricity. There were no emissions from the transportation of the printer because it was printed in the headquarters of the company.

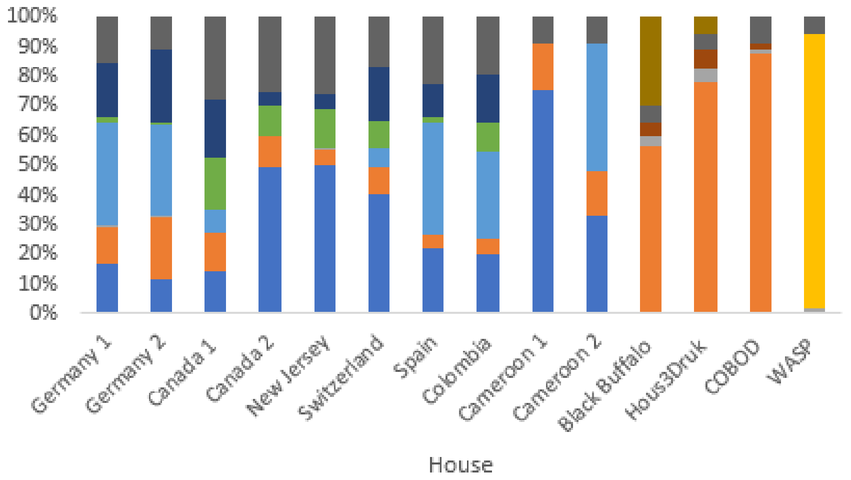


Figure 3. Contribution of single building materials and energy to the total emissions of CO_2eq/m^2 from each house, expressed as a percentage.

The previous analysis allowed to identify concrete, cement, and bricks as the main contributors to GHG emissions from the construction of buildings. Since most of the emissions from concrete depends on cement, the impact on GHG emissions of changing the type of cement used in two case studies was calculated. As shown in Figure 4, the emissions from the 3D-printed house were mostly influenced by the type of cement. Using mortar cement resulted in 48.1 kg CO2 eq/m2, while a mix with 6 to 20% of limestone emitted 130 kg CO2 eq/m2. The SD of the values relative to the CO_2 eq/m^2 chenging the type of cement was 24.02 for the conventional house. For the conventional building, using 45% of alternative constituents lowered the emissions the most, resulting in 151.00 kg CO2 eq/m2, while the highest value was 172 kg CO2 eq/m2 from the use of 6-20% of alternative constituents. Overall, the emissions from the 3D-printed house showed less variability, as indicated by the SD of 6.38.

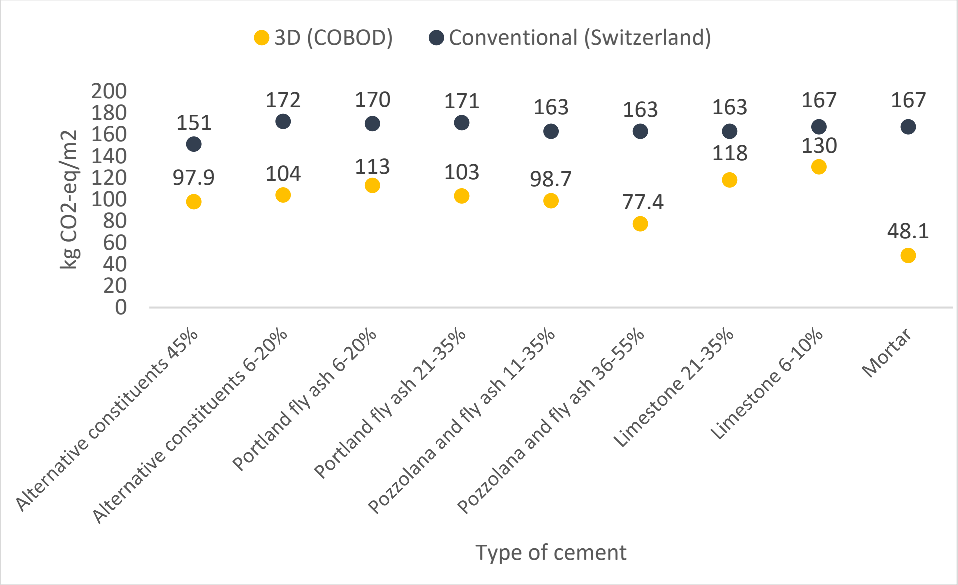


Figure 4. CO2-eq emissions associated with the use of different types of cement to prepare the concrete employed to 3D-print a house.

Effect on the atmosphere

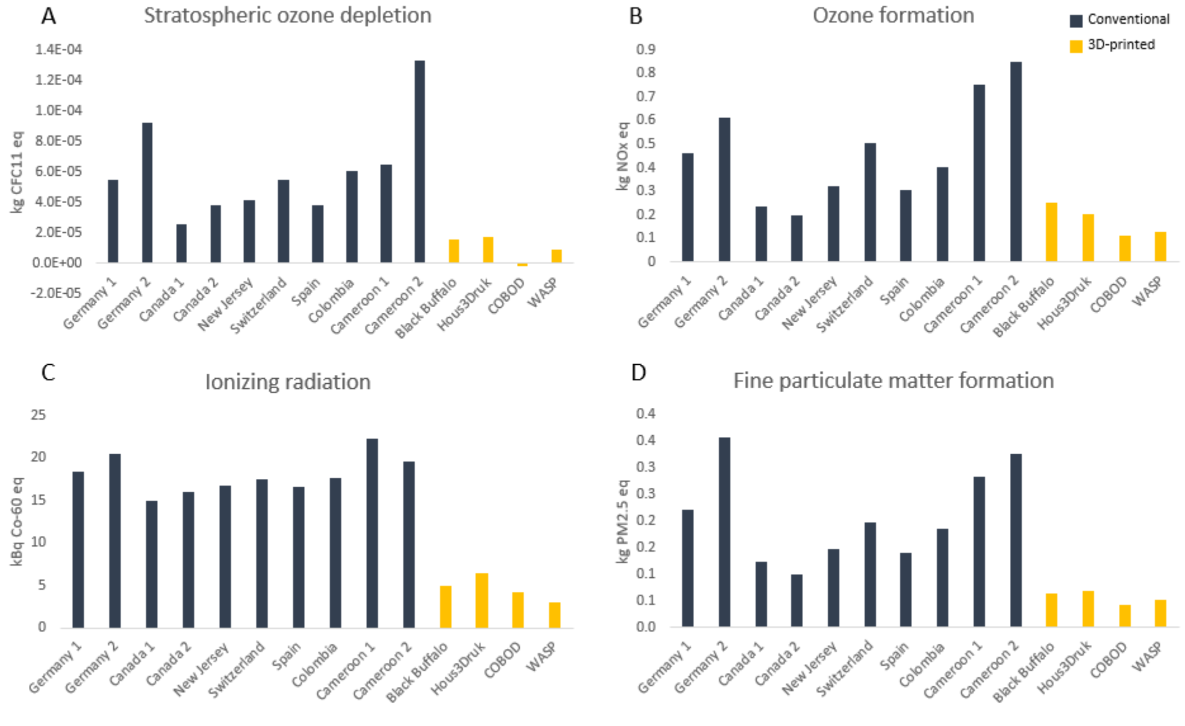


Figure 5. Contribution of conventional (black bars) and 3D-printed (yellow bars) buildings to stratospheric ozone depletion (A), indicated as kg CFC11 eq, ozone formation (B), indicated as kg NOx eq, ionizing radiation (C), indicated as kg Co-60 eq, and fine particulate matter formation (D), expressed as kg PM2.5 eq.

Stratospheric ozone depletion, ozone formation, ionizing radiation, and fine particulate matter formation were considered to quantify the impacts of the case studies on the atmosphere. Figure 5A shows the ozone depletion potential expressed in kg of CFC-11 eq. The 3D-printed buildings presented lower contributions than the conventional buildings, with average values of 1.01-05 kg CFC-11 eq and 6.04-05 kg CFC-11 eq respectively.

Particularly low was the value for COBOD, with -1.81E-06 kg CFC-11 eq. The low value was associated with the depletion potential of the cement used to print the house (Figure 6A), which was a mix of mortar and recycled roofing tiles. COBOD was the only example where this formulation was used. In conventional buildings, bricks, electricity, and timber were the greatest contributors to ozone depletion. The CFC-11 eq were the greatest for the Cameroon 2 house, which was almost entirely built out of bricks. In the case studies where none of these was used, concrete and cement contributed the most. To 3D-print WASP, only locally sourced natural materials were used, so the main impact in terms of ozone depletion came from lime.

Ozone formation is expressed in kg of NOx equivalents. The contribution from the buildings is shown in Figure 5B, and the average value was 0.47 kg NOx eq for conventional buildings and 0.17 kg NOx eq for 3D-printed ones. The two conventional houses from Cameroon had the greatest contribution in terms of ozone formation, followed by Germany 2. In Cameroon 1, concrete was the main contributor, while in Cameroon (bricks) it was bricks, followed by concrete. In both cases, the remaining emissions are associated with cement and electricity (Figure 6B). In the case of Germany 2, the emissions were almost equally distributed among bricks, concrete, and steel, and followed by concrete and electricity (Figure 6B). Out of the 3D-printed houses, COBOD and WASP showed the lowest values for ozone formation, while Hous3Druk and Black Buffalo had similar contributions to those from the conventional buildings Canada 1 and Canada 2, with 0.21 ,0.25, 0.23, and 0.20 kg of NOx equivalents emitted respectively (Figure 5B). About 50% of the emissions from Black Buffalo came from the transportation of the 3D-printer to the printing site, with the rest deriving mostly from the use of cement (Figure 6B). Cement was the main source of NOx equivalents in Hous3Druck. For Canada 1 and 2, the greatest percentage of emissions depended on timber and electricity, as well as concrete and cement. The emissions from WASP came almost entirely from lime.

The ionising radiation is measured in Cobalt-60 equivalent to air and the results are shown in Figure 5C. The values are way higher for the conventional buildings, with an average of 180.30 kg Co-60 equivalent against that of 18.66 of 3D-printed buildings. 60 to 95% of the contribution from conventional buildings came from the use of electricity (Figure 6C). Electricity was also one of the main contributing factors for 3D-printed buildings, especially for WASP, where it represented 70% of the emissions. The value dropped to 50% in COBOD and to around 30-40% in Hous3Druk and Black Buffalo. Cement was responsible for almost all the remaining contribution (Figure 6C).

Fine particulate matter formation is expressed as kg primary PM2.5 equivalents. The results are presented in Figure 5D. The contribution of the 3D-printed houses was always lower than that of the conventionally built ones, and the mean value was 0.06 kg PM2.5 for the first ones and 0.21 for the latter. COBOD showed the lowest contribution with 0.04 kg of PM2.5 equivalent produced, while the two buildings in Cameroon and Germany 2 were amongst the greatest contributors, with respectively 0.28, 0.33, and 0.36 kg of PM2.5 eq. Cement was the main contributor to fine particulate matter formation for COBOD, Hous3Druk and Black Buffalo. Concrete was the main one in Cameroon 1 and a relevant contributor for Cameroon 2. Brick was the main one in Cameroon 2 and along with cement and steel, a big contributor in Germany 2.

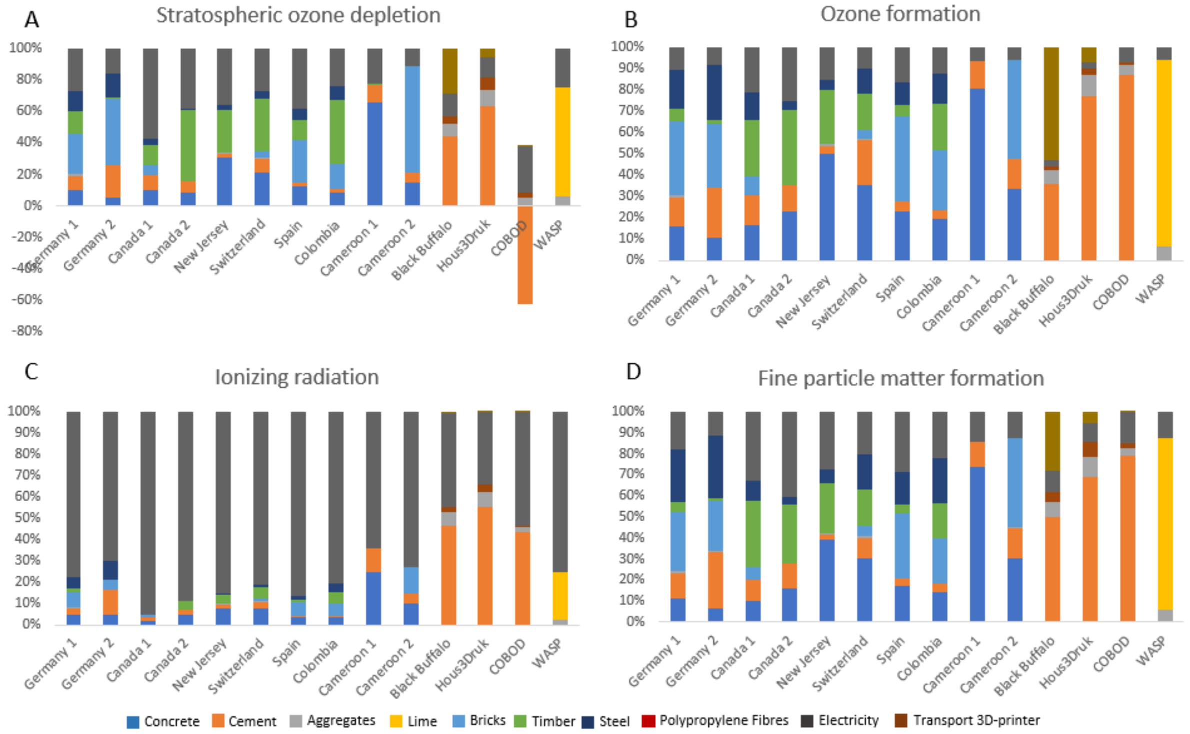


Figure 6. Contribution of single building materials and energy to stratospheric ozone depletion (A), ozone formation (B), ionizing radiation (C), and fine particulate matter formation (D).

Effect on ecosystems

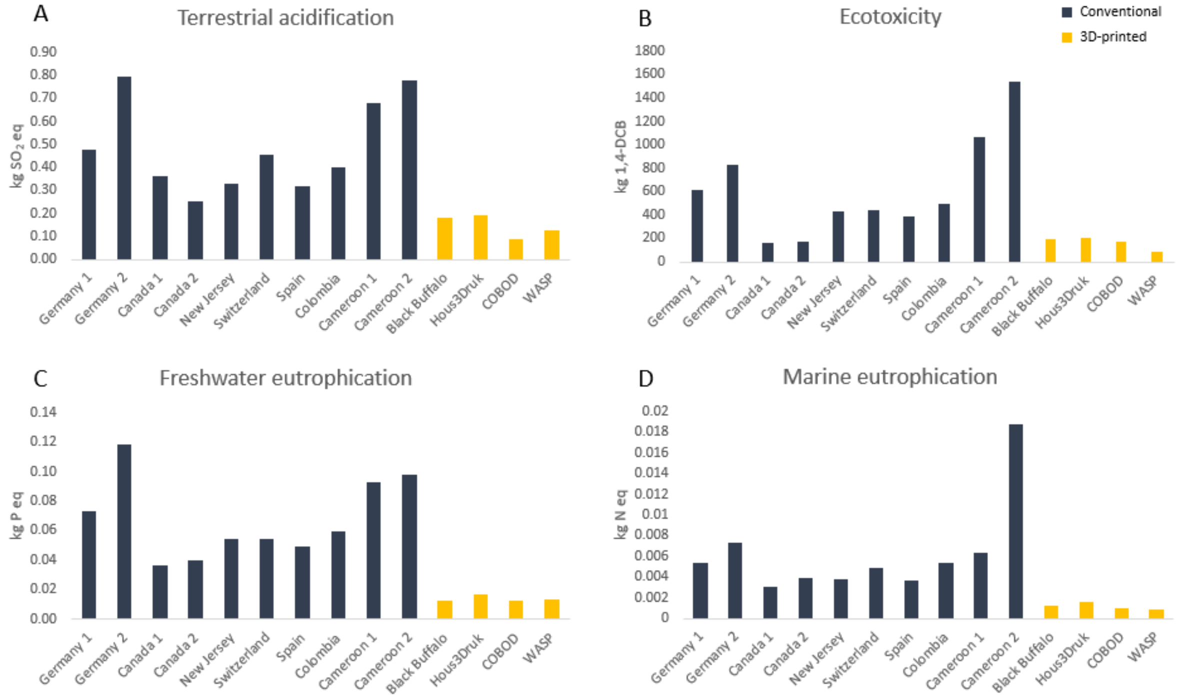


Figure 7. Contribution of conventional (black bars) and 3D-printed (yellow bars) buildings to terrestrial acidification (A), indicated as kg SO_2 eq, ecotoxicity (B), indicated as kg 1,4-DCB, freshwater eutrophication (C), indicated as kg P eq, and marine eutrophication (D), expressed as kg N eq.

Terrestrial acidification, ecotoxicity, freshwater and marine eutrophication were assessed to determine the impacts of the different types of buildings on the ecosystems. The impact of conventional buildings on terrestrial acidification, expressed in kg of SO_2 equivalent, was found more prominent than the impact of 3D-printed houses. The average contribution was 0.48 kg SO_2 eq for conventionally built houses and 0.14 kg SO_2 eq for 3D-printed houses (Figure 7A). As shown in Figure 8A, bricks, timber, and concrete are the main contributors to terrestrial acidification for conventional buildings, while cement is the main one for 3D-printed houses.

Ecotoxicity is expressed in kg of 1,4-dichlorobenzene-equivalents (1,4DCB eq). Figure 7B provides the combined contribution of the houses to terrestrial, freshwater, and marine toxicity. The mean value for conventional buildings is 613.61 kg 1,4 DCB eq, and 163.08 kg DCB eq for 3D-printed houses. Canada 1 and 2 show a modest contribution to ecotoxicity, and mainly due to electricity (Figure 8B). Cement is the main cause of ecotoxic effect for all the 3D-printed houses apart from WASP (Figure 8B).

Freshwater eutrophication is expressed in kg of P equivalent and the average contribution was 0.07 kg P eq for conventional buildings and 0.01 kg P eq for 3D-printed ones. Electricity is a great contributor to it in conventional buildings, as well as concrete and cement, while cement or lime were the main one for 3D-printed houses (Figure 8C).

Conventional houses showed greater impacts on marine eutrophication than 3D-printed ones. Marine eutrophication is expressed in kg N equivalent, and the average contribution was 0.006 kg N eq from conventionally built houses and 0.001 kg N eq from 3D-printed ones (Figure 7D). The contribution from the single materials is similar to that on freshwater eutrophication, with electricity playing a significant role for conventional buildings and cement for 3d-printed ones (Figure 8D).

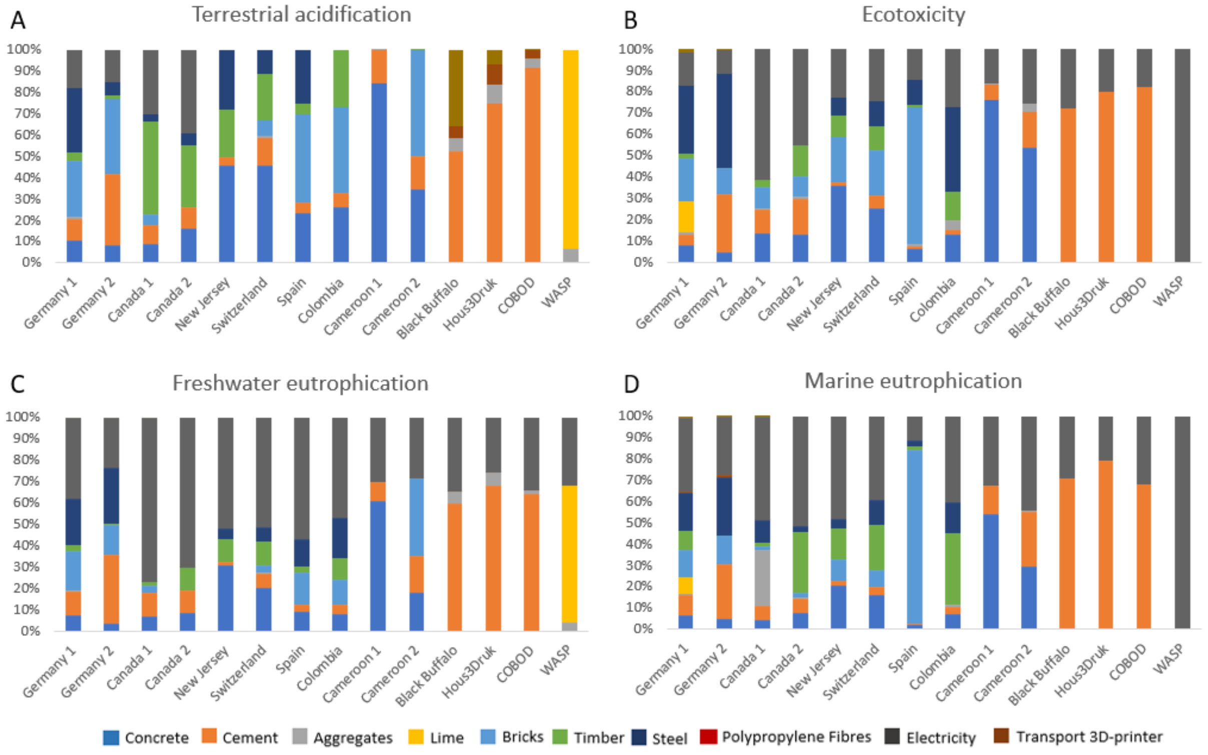


Figure 8. Contribution of single building materials and energy to terrestrial acidification (A), ecotoxicity (B), freshwater eutrophication (C), and marine eutrophication (D).

Effect on humans

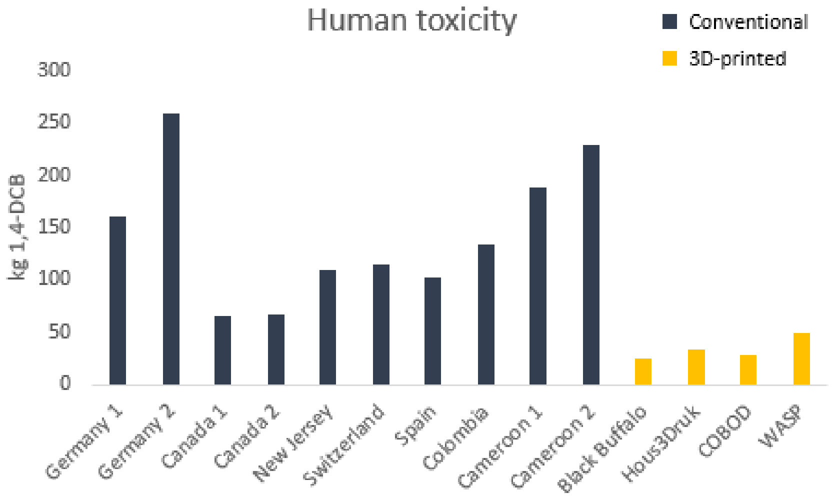


Figure 9. Contribution of conventional (black bars) and 3D-printed (yellow bars) houses to human toxicity, expressed as kg of 1,4-DCB eq.

Human toxicity was expressed as kg of 1,4-Dichlorobenzene (1,4-DCB), and the average values found in the analysis were 143.17 kg 1,4 DCB for conventional buildings and 34.53 kg 1,4 DCB for 3D-printed ones (Figure 9). Steel, electricity, or concrete were responsible for the greatest contribution in conventional buildings, while cement was the main one in 3D-printed houses. electricity was the only contributor for WASP.

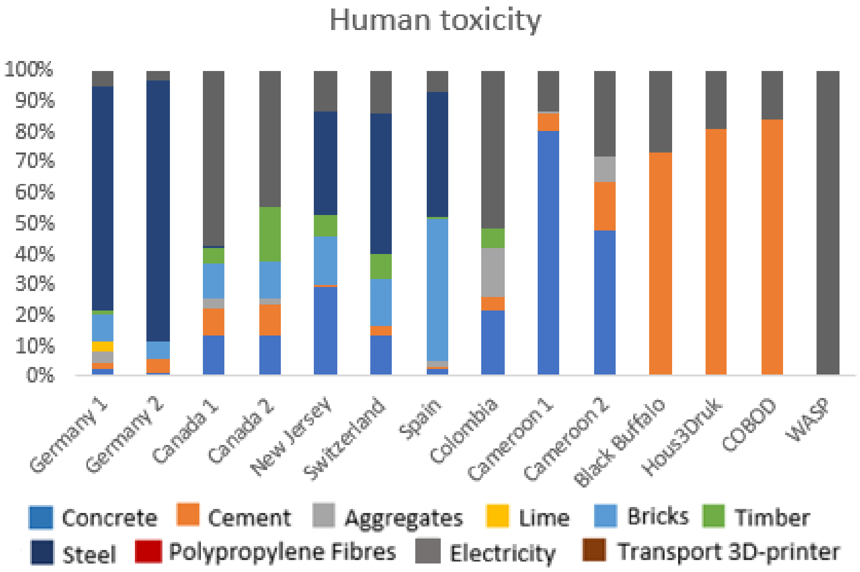


Figure 10. Contribution of single building materials and energy to human toxicity.

Resource use

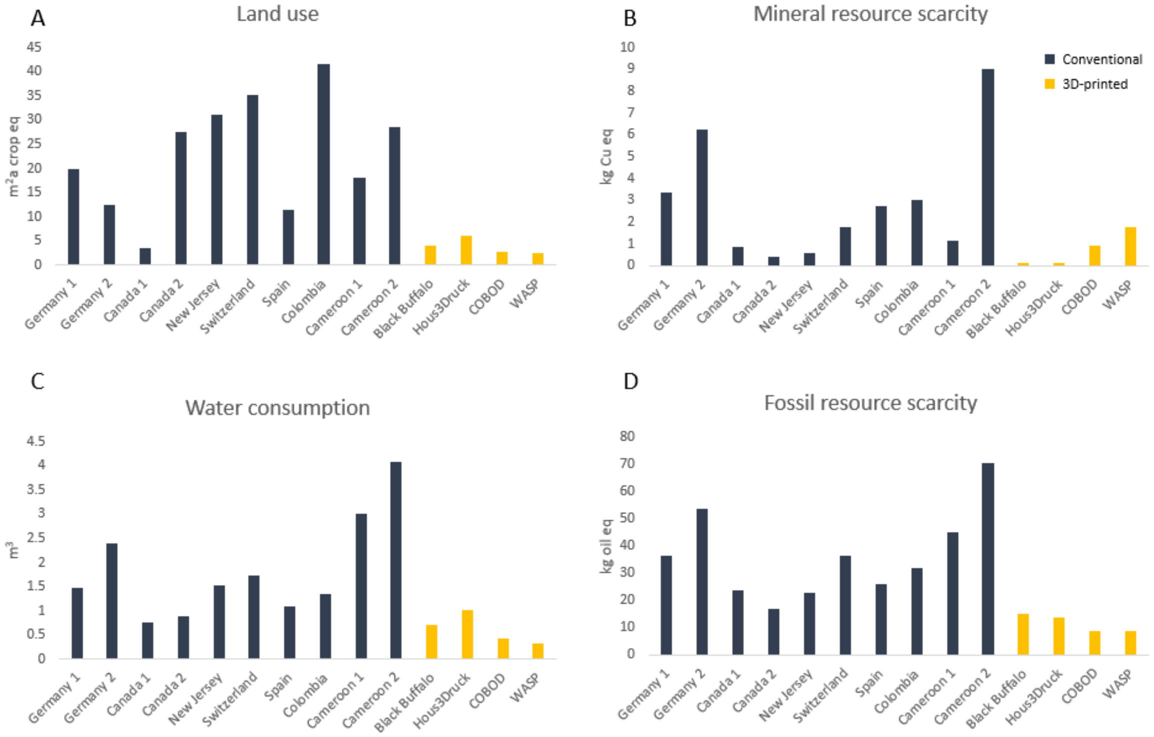


Figure 11. Contribution of conventional (black bars) and 3D-printed (yellow bars) buildings to land use (A), indicated as m^{2}a crop eq, mineral resource scarcity (B), indicated as kg Cu eq, water consumption (C), indicated as m^3, and fossil resource scarcity (D), expressed as kg oil eq.

The influence of the buildings on resource use was assessed from the impact of the houses on land use, mineral resource scarcity, water consumption, and fossil resource scarcity. Land use is expressed in m^2·yr annual crop equivalents and refers to the relative species loss caused by a specific land use type. The mean contribution to land use change is 12.03 m^{2}a crop eq for conventional buildings and 3.88 m^{2}a crop eq for the 3D-printed ones (Figure 11A). An important share of the impact from conventional buildings (Germany 1, Canada 2, USA, Switzerland, Spain, Colombia) comes from the use of timber (Figure 12A).

Mineral resource scarcity is quantified in Surplus Ore Potential (SOP), expressed as kg Cu-eq. The SOP expresses the average extra amount of ore produced in the future caused by the extraction of a mineral resource considering all future production of that mineral resource (Vieira et al. 2016a). Conventionally built houses were shown to contribute more than 3D-printed ones, with an average of 2.92 kg Cu eq for the first one and 0.73 kg Cu eq for the latter (Figure 11B). Steel, bricks, and concrete are the main responsible for the impact of conventional buildings on mineral scarcity, while cement and aggregates are the main ones for 3D-printed houses (Figure 12B).

The category water use represents m^3 of water *consumed* per m^3 of water *extracted*. 1.83 m^3 is the mean value for conventional buildings (Figure 11C), with electricity and concrete or cement being the main contributors (Figure 12C). The mean value drops to 0.63 m^3 for 3D-printed buildings (Figure 11C) and cement or lime and aggregates are responsible (Figure 12C).

Finally, fossil resource scarcity is determined as the Fossil Fuel Potential (FFP in kg oil-eq), and the mean contribution was 36.23 kg oil eq for conventional buildings and 11.55 for 3D-printed ones (Figure 11D). Transport of the 3D-printer is an important contributor for Black Buffalo, while cement or lime were the main ones in the other 3D-printed houses (Figure 12D). For the conventional buildings, all the various components contribute in similar percentages to the overall impact (Figure 12D).

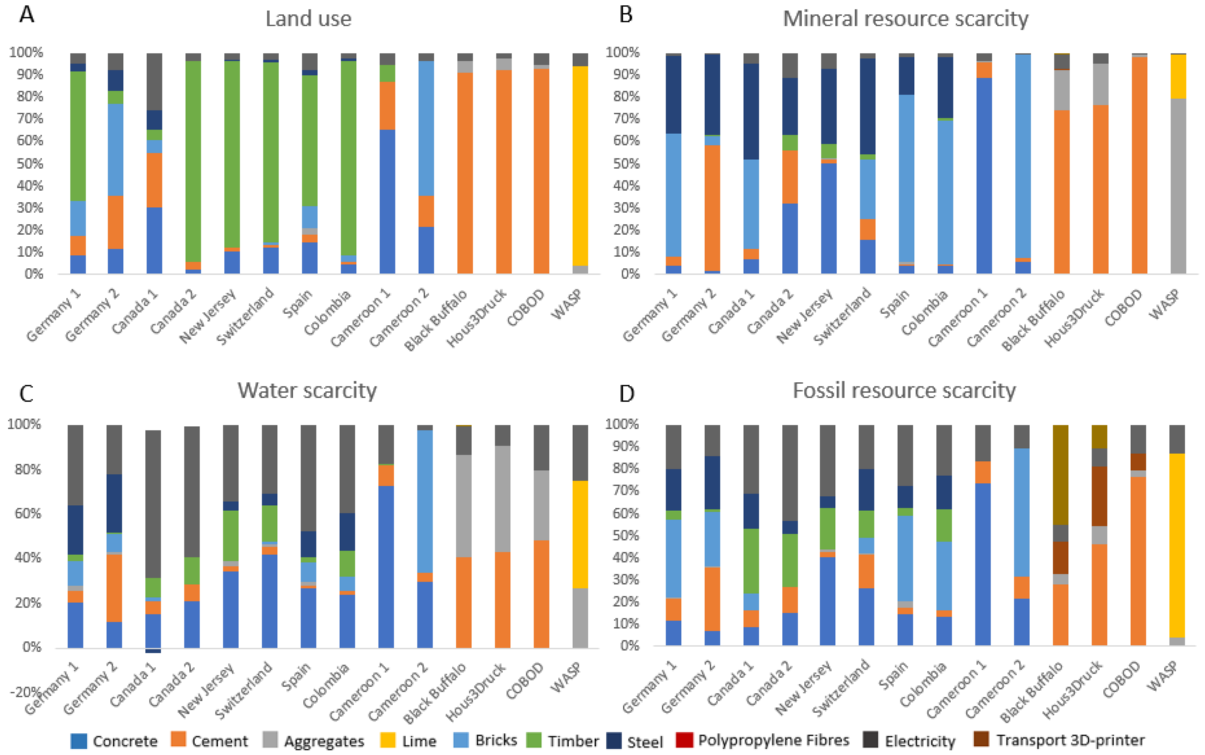


Figure 12. Contribution of single building materials and electricity to land use, mineral resource scarcity, water scarcity, and fossil resource scarcity.

Endpoint

Damage to human health, ecosystems, and resources are used as endpoint indicators.

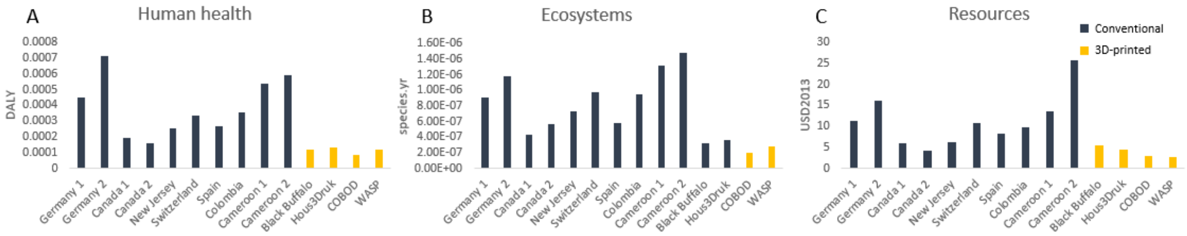


Figure 13. Contribution of conventional (black bars) and 3D-printed (yellow bars) buildings to damage on human health (A), indicated as DALY, ecosystems (B), indicated as species lost per year, and resources, expressed as USD2013.

Damage to human health is expressed in disability-adjusted life year (DALY), which is the number of years lost due to ill-health, disability or early death. 3D-printed houses have a lower impact on human health compared to conventionally built ones. The means of the days of years lost is 0.000114 for 3D-printed buildings and 0.000386 for conventional houses (Figure 13A). The damage to ecosystems is expressed in species lost per year, and the mean value was 9.14^{-07} for conventional houses and 2.95^{-07} for 3D-printed ones (Figure 13B). The damage to resources is expressed in US dollars. The mean value was lower for 3D-printed houses (3.976941 USD2013) than for conventional buildings (11.16939 USD2013) (Figure 13.C).

Table 3 provides an overview of all the environmental impact categories and the average contribution of conventional and 3D-printed buildings. It also shows that the difference between the averages is statistically significant.

Table 3. Summary table with the average values of conventional and 3D-printed houses for each impact category. The last column shows the p-value for the t-tests that compared the average value for conventional and 3D-printed houses. If p-value <0.05, the averages are not equal.

Impact category	Unit	Conventional house	3D-printed house	P(T<=t) two-tail
Global Warming	kg CO2 eq	173.3	68.8	0.002267
Stratospheric ozone depletion	kg CFC11 eq	6.0E-05	1.0E-05	0,0000596
Ionizing radiation	kBq Co-60 eq	18.0	4.7	1.11E-06
Ozone formation	kg NOx eq	0.5	0.2	0.002447
Fine PM formation	kg PM2.5 eq	0.2	0.06	0.00034
Terrestrial acidification	kg SO2 eq	0.5	0.1	0.000358
Freshwater eutrophication	kg P eq	0.07	0.01	0.000166
Marine eutrophication	kg N eq	0.006	0.001	0.007061
Ecotoxicity	kg 1,4-DCB	613.6	163.1	0.008095
Human toxicity	kg 1,4-DCB	143.2	34.5	0.000497
Land use	m2a crop eq	23.0	3.9	0.000549
Mineral resource scarcity	kg Cu eq	2.9	0.7	0.041067
Fossil resource scarcity	kg oil eq	36.2	11.5	0.000787
Water consumption	m3	1.8	0.6	0.006284

Applicability of 3D-printing in developing countries

Interviews were conducted to determine the feasibility of using 3D-printing as a method to provide housing in developing countries. The interviews focused on the limitations the experts saw to the applicability of 3D-printing in developing countries and on how to overcome them. Limitations in four main areas were identified thanks to the responders. The first problem is the availability of adequate materials used by the 3D-printer. Suitable materials need to meet specific requirements in terms of printability and resistance. The availability of such materials in developing countries and the higher cost compared to conventional concrete were indicated to be a limitation by all 3 interviewees. As stated by architect Carlos Gonzales Cabrera, the same problem would arise with the availability of 3D-printers themselves. He thinks that investments in the technology could be helpful to overcome this limitation.

Environmental law expert Jadille Mussa Castellano also pointed out that legislation has struggled to adapt to the rapid advancements of 3D-printing in construction and often falls behind, especially in developing countries. According to her, the environmental norms currently at place in Chile for conventional buildings to access the “Sistema de Evaluación Ambiental” (environmental evaluation system) could also be applied to the 3D-printed ones. The legal gap concerns the printing materials used, especially if 3D-printed houses are conceived as a sustainable and environmentally friendly alternative to conventional construction. It is fundamental to gain a better understanding of what materials are used and how they are disposed of to actually determine the short- and long-term sustainability of 3D-printed projects. Once that is established, it will be possible to include the materials in the “Ordenanzas de Urbanismo y Construcción” (decrees of urbanism and construction) of the “Ministerio de Vivienda y Urbanismo” (ministry of urban planning). I3 does not see the current legal gap as a great limitation to the future applicability of 3D-printing in construction, as the more common it will become, the faster policymakers will adapt. In respect to developing countries, a possibility to speed up the adaptation process could be to adopt the same standards and regulations of countries that have more up to date policies in the construction sector.

Gonzales Cabrera, on the other hand, thinks that the legal gaps are symptomatic of another limitation to the applicability of 3D-printing, which is cultural resistance to innovation, and especially when it comes to housing. He thinks that a problem is that industrialisation is seen as something ephemeral, while housings are perceived as something that needs to last for life. He does not think that this limitation can be overcome in the short term, but a solution could be that the State adopts a mass housing policy using 3D-printing. This would allow to demonstrate the effectiveness of the technology and defeat the cultural resistance.

The last aspect that was pointed out as problematic for a large-scale application of construction 3D-printing in developing countries is the impact on the labour market. When asked about this topic, the interviewees agreed that less workers are needed to 3D-print a building compared to conventionally constructing it. Moreover, the workers need to be more specialised to be able to operate the printer. Less people on the building site also results in a decrease in the number of accidents and an overall increase in safety. Nonetheless, it is not clear how it would affect the workers, which could lose their jobs. According to Gonzales Cabrera, the loss in jobs is one of the reasons why he does not think that a large-scale incorporation of construction 3D-printing in developing countries is likely to happen in the short run. He thinks that the solution would be once again to win the cultural resistance around industrialisation in construction. He still thinks that some sort of industrialisation in construction is inevitable, but he is not sure it will happen in the short or medium-term. It could be that the use of 3D-printing will start in small sectors and addressed to medium and high socio-economic levels. Civile engineer Janee A. Jagoda thinks that 3D-printing is still relatively small-scale in terms of footprint and number of floors, so large-scale construction will not be impacted until the technology scales up accordingly. This could give the time to the construction industry to adapt and to invest in the specialisation of workers in the design/programming side of construction. Another possibility is that some workers might transition to larger projects. She also pointed out that at the moment the interview was conducted (may 2022), the US are experiencing a construction boom, with not enough workers to meet the demand for new homes and projects. If developing countries will follow a similar pattern, there will be no shortage of work for employees to transition to. She actually sees fewer limitation to the applicability of large-scale 3D-printing in developing countries than developed ones because the need for safe, quality structures and the lack of regulations open a window for the technology.

Discussion

The goal of the study was to determine the environmental impacts of 3D-printed houses and to compare them with conventionally constructed buildings. Moreover, the applicability of the technology to provide sustainable housing in developing countries was assessed. As discussed in the results section, 3D-printed houses performed better than the conventional ones in all the considered impact categories. Concrete and cement together represented on average 65% of the materials used for walls and foundations of conventional houses, and along with bricks, they were often the main contributors to the environmental impacts. Looking, for instance, at the contribution to global warming, on average 44% of the CO_2 eq emissions could be attributed to them. The main factor that was found to cause emissions from concrete was the production of cement. The overall emissions from conventional buildings did not appear to change much by changing the type of cement used but changed in 3D-printed houses. This can be explained by the fact that cement was the main component of the mix used for printing 3 out of the 4 considered buildings. Using mortar cement showed the greatest potential in terms of emissions reduction, but it also tends to be a more expensive option; mortar used in 3D-printing is usually available as a dry mix that needs to be combined with water. The pre-drying process is expensive, therefore these materials are typically used for small buildings (COBOD, 2020).

Bricks, when used, are also responsible for a large portion of environmental impacts. They account for roughly 50% of the contribution to mineral resource scarcity, 30% to global warming, ozone depletion, ozone formation, and mineral resource scarcity, 24% to terrestrial acidification, 22% to fine particulate matter formation. Same as for concrete, the great contribution to environmental impacts of bricks comes more from the large amount used rather than from the material itself (Huang et al., 2019). A solution for this would be to use more eco-friendly alternatives such as bricks made from locally sourced materials. A study from 2020 found that replacing fire clay bricks with sun-dried ones can result in a reduction by 5907 kg CO_2 eq and 5305 MJ every 1000 bricks (Dabaieh et al., 2020). 3D-printed houses do not need bricks, nor most of the other building materials used in conventional houses, and this partly explains the lower environmental impacts. Moreover, the printing material needs to meet specific requirements, such as being liquid enough to pass through the nozzle of the printer and yet solidifying fast enough to allow the layer-by-layer deposition, assuring adherence between the layers, and avoiding deformations or shrinkage after the solidification (Siddika et al., 2020). This can be challenging for 3D-printing companies but also leaves space for personalisation.

Many companies declare to be looking for formulations that in addition to meeting the printability requirements are also environmentally friendly. An example of this is COBOD, which replaced part of the cement used to print the COBOD house with recycled roofing tiles accordingly adapted to be incorporated in the printing mix (COBOD, 2020). This is likely to explain the negative value of COBOD in respect of the contribution to ozone depletion. The negative contribution is due cement, and the only difference between the cement used for COBOD and the one used for Black Buffalo and Hous3Druck is in the roofing tiles. Another example in terms of experimentation with different materials is WASP. It is an Italian company that puts a lot of focus on being as sustainable as possible, so they use local material sourced from the soil surrounding the printing site as building materials and rice straw for insulation; they also use a 3D-printer that only needs some solar panels to function (WASP, 2022). In the case of WASP, most of the environmental impacts came from the extraction and use of lime, but since they use locally sourced materials, the impacts could vary based on the location of the printing.

Electricity was also found to be an important contributor to some environmental impacts, especially for conventional buildings. The most relevant contribution was to ionizing radiation, global warming, eutrophication, human toxicity, and water and fossil fuel scarcity. The ionizing radiation from electricity is mostly dependent on uranium mill tailings, waste products of the milling process which contain long-lived radioactive isotopes. The other environmental categories are mostly impacted by the use of fossil fuels for the generation of electricity. The energy consumed during the construction phase represents 7 to 15% of the embodied energy of a conventional building, and it is mainly coming from transporting the materials and operating equipment and tools (Pullen, 2000). The electricity consumed in the construction of 3D-printed houses comes from the operation of the printer and of the control unit that regulates the printing process (Abdalla et al., 2021).

Steel is only used in conventional buildings and has a particularly strong effect on human toxicity and mineral resource scarcity. The effect on human toxicity is both carcinogenic and non-carcinogenic and it mainly caused by the sintering operations and in particular by the emissions of heavy metals, dioxins and polychlorinated dibenzofurans associated with it (Renzulli et al., 2016). In 3D-printed buildings, steel can be replaced by polypropylene (PP) fibres (Nematollahi et al., 2018). Their contribution to the various environmental impacts is relatively low, apart from that to fossil resource scarcity, due to it being a polymer obtained from propene, hence a hydrocarbon.

The use of timber in conventional construction is an environmentally friendly alternative to other materials, but it still comes with some negative impacts. The main problem with the use of timber is relative to its impact on land use, caused by the space that is needed for the trees to grow.

Overall, 3D-printed houses showed significantly lower contributions than conventional buildings to all the environmental categories considered in the study, both in terms of mid- and end-point indicators. This finding is in accordance with previous studies conducted on the same topic (Abdalla et al., 2021; De Schutter et al., 2018; Oberti et al., 2015; Tay et al., 2017). In addition to the benefits in terms of sustainability, the potential of additive manufacturing in construction also lays in it being a cheaper option than conventional building methods. Another benefit is that using additive manufacturing techniques, buildings can be printed in a few hours and less, but more specialised workers are needed to complete the process. All this makes 3D-printing an interesting possibility to provide sustainable housing in developing countries. The interviews conducted with experts confirmed this option, but also highlighted some drawbacks. First, the need of special materials can be an asset since it allows for purpose-driven personalisation of the printing mix; numerous studies evaluated the performances of different formulations (Asprone et al., 2018; Gosselin et al., 2016; Khan, 2020; Lowke et al., 2018; Mohan et al., 2021). On the other hand, it can be a limitation to the applicability in developing countries because of material availability and higher costs. As it was pointed out during one of the interviews, the availability of the 3D-printer itself can be a problem since it needs to be transported. The transport can be problematic for the lack of adequate infrastructures in some areas, especially in developing countries. Even if the transport is feasible, it can be very energy intensive: construction 3D-printers weigh varies a lot (Table 2), and if the transportation distance is very long, the environmental impacts associated with the construction of the building can increase. It was the case of Black Buffalo, as the contribution to the overall environmental impacts of the transportation of the printer is often way higher than the other printed buildings (Figures 3, 6A, 6B, 6D, 8A, 12D). One of the interviewees pointed out that investments from the local governments could help overcoming this problem, along with defeating the cultural resistance. If 3D-printed houses start to be seen as a sound and attractive option, construction companies might choose it over conventional methods. This would however require some time, so the large-scale use of this technology in developing countries seems unlikely in the short and maybe even medium run. The construction industry is generally characterised by low innovation rates (Novikov, 2014), mainly due to low investments in the technological aspects, and the high fragmentation of the construction projects, which impedes the automation process of the industry (Hossain et al., 2020). More automation would increase the safety of the final product, since the error associated with manual labour could be eliminated. The elimination of construction flaws would result in a reduction of the project costs. The rework costs associated with resolving construction defects alone accounts for 5 to 15% of the total cost of a project (Adaloudis et al., 2021). The productivity would also be increased because the equipment could operate when manual work would usually stop, such as at night or in harsh environmental conditions (Weng et al., 2020).

On the other hand, introducing additive manufacturing techniques in the construction sector would result in a reduction in the number of workers needed to complete a project. This can have a positive impact in terms of safety of the workers, since the construction sector is generally associated with poor safety conditions, resulting in high accidents and fatality rates (Ringen et al., 1995). Moreover, the workers would need to be more specialised, resulting in higher salaries and better overall working conditions. It is not clear whether the need for less, but more specialised workers would result in a loss of jobs. In developed countries, the construction industry is experiencing a shortage of labourers; in the Netherlands, for instance, it relies heavily on seasonal foreign labour, cheaper than the national one. The problem with this is that this trend is not going to be sustainable in the long run because the seasonal's workers countries of origins are expected to experience economic growth, and labour cost will increase (Adaloudis et al., 2021). As pointed out by I3, the US is experiencing a similar issue, with labour no longer meeting the sectorial demand. In this scenario, the introduction of 3D-printing could be an attractive option for people to have access to jobs in the construction sector that would be safer and better paid than traditional ones.

Overall, the present study showed that 3D-printing in construction comes with many challenges and limitation, which would require investments and a cultural shift to be overcome if we want to successfully use the technology in developing countries. Nonetheless, it also presents numerous possibilities to make the construction sector more efficient, safe, and productive than it is now. It would also significantly mitigate the negative environmental impacts that make construction one of the main contributors to climate change and pollution.

Limitations and further research

The main limitation of the study was data availability of the materials used for 3D-printed houses. Many 3D-printing companies that work in construction were contacted and asked if they wanted to share data to assess their environmental contributions, but only four out of more than fifteen decided to participate, despite the guarantee of anonymity if they needed it. Having more data would have allowed for a more balanced and comprehensive comparison between conventional and 3D-printed buildings.

Another limitation was that SimaPro, like all LCA software, works based on assumptions. To estimate the environmental impacts, three different cultural perspectives can be chosen to represent reality. The hierarchist perspective, which is based on the most common policy principles with regards to time-frame and other issues, was chosen over the others available, but reality is always more complex than models (PRé Sustainability et al., 2020). Moreover, even when data on building materials was available, it was often generic (concrete, cement, sand, bricks, etc), so approximations were made when choosing the inputs in SimaPro.

In spite of the limitations, the results showed significant differences for 3D-printed and conventional houses. This means that even if the approximations and assumptions made the estimates less reliable, they still provide a solid indication of the differences in the environmental impacts. Further research could take some results of this study as a starting point and expand the system boundaries. The present study focused on the construction phase, and in particular on the building materials used for walls and foundations. Including more structural components and other life-phases of the buildings would provide more comprehensive results and a better overview of the real environmental impacts.

Conclusions and Recommendations

The goal of the study was to determine the environmental impacts of 3D-printing houses and to compare it to that of building them with conventional construction techniques. Moreover, the applicability and limitations of 3D-printing to provide sustainable housing in developing countries was assessed. To determine and compare the environmental impacts of 3D-printed and conventional buildings, fourteen case studies were selected. Ten case studies were conventional buildings, and four were 3D-printed ones. Life Cycle Assessments (LCA) were performed on the material extraction and construction phases of the houses, using ReCiPe 2016 as impact assessment method and 1 m^2 of building as a functional unit. Since only foundations and walls can be 3D-printed, these were the components considered in the analyses. The environmental impacts were assessed at mid- and endpoint level. The four 3D-printed houses performed significantly better than the conventional ones in all the impact categories, both in terms of midpoint and endpoint indicators. Bricks, concrete, and cement were the building materials that majorly contributed to the environmental impacts of conventional buildings. Electricity was also often associated with high environmental impacts, especially in ionising radiation, global warming, eutrophication, human toxicity, and water and fossil fuel scarcity.

To determine the viability of using 3D-printing construction in developing countries, 3 experts were interviewed and asked about the main limitations and how to overcome them. The most important challenges that were identified were in terms of materials availability, lack of codes and regulations, cultural resistance towards innovation in the construction sector, and uncertainty in the response of the labour market to the introduction of the technology. It was suggested that the investments in the technology and the utilisation of it on small-scale projects might help overcome the cultural resistance. Investments would also be required to acquire the printers and the appropriate materials. The way that the labour market could adapt to more automation in the construction sector will depend on many factors. Some developed countries are facing a shortage of construction workers, and if developing countries will follow the same trend, 3D-printing could create roles for skilled construction workers that would be attracted by the better and safer working conditions compared to conventional buildings.

The findings from this research showed the potential of 3D-printing for construction, and proved its feasibility for developing countries, if action is taken by various stakeholders to overcome the limitations. The research also leaves a lot of space for future development. The environmental impacts were only determined for part of the life cycle of the buildings. it would be interesting to calculate the environmental contribution from cradle-to-grave and particularly during the operational phase. It would be interesting, for instance, to know if 3D-printed houses performed better in terms of energy use because of the different materials used compared to conventional buildings. Another development could be to consider more case studies of 3D-printed houses, and maybe even see how the use of different 3D-printers or materials would influence the environmental impacts. Moreover, it could be interesting to further investigate the potential of 3D-printing for developing countries. For this purpose, more people could be interviewed. it would be useful to have the perspective of NGOs that work with housing, or of economists and sociologists to fully understand the social implications that the technology could have.

References

Abanda, F. H., Nkeng, G. E., Tah, J. H. M., Ohandja, E. N. F., & Manjia, M. B. (2014). Embodied Energy and CO2 Analyses of Mud-brick and Cement-block Houses. *AIMS Energy, 2*(1), 18-40. doi:10.3934/energy.2014.1.18

Abdalla, H., Fattah, K. P., Abdallah, M., & Tamimi, A. K. (2021). Environmental Footprint and Economics of a Full-Scale 3D-Printed House. *Sustainability, 13*(21), 11978. Retrieved from https://www.mdpi.com/2071-1050/13/21/11978

About SimaPro. (2022). Retrieved from https://simapro.com/about/

Adaloudis, M., & Bonnin Roca, J. (2021). Sustainability tradeoffs in the adoption of 3D Concrete Printing in the construction industry. *Journal of Cleaner Production, 307*, 127201. doi:https://doi.org/10.1016/j.jclepro.2021.127201

Ali, E. (2019). Life Cycle Assessment of 3D Printing Houses.

Ametepey, S. O., & Ansah, S. K. (2015). Impacts of Construction Activities on the Environment: The Case

of Ghana. *Journal of Environment and Earth Science, Vol.5, No.3*.

Asprone, D., Auricchio, F., Menna, C., & Mercuri, V. (2018). 3D printing of reinforced concrete elements: Technology and design approach. *Construction and Building Materials, 165*, 218-231. doi:https://doi.org/10.1016/j.conbuildmat.2018.01.018

Cassell, C. (2005). Creating the interviewer: identity work in the management research process. *Qualitative Research, 5*(2), 167-179. doi:10.1177/1468794105050833

COBOD. (2020). BOD2 Specifications. Retrieved from www.cobod.com

COBOD. (2022). COBOD FAQ - What is The Construction Process When Using a 3D-Printer. Retrieved from https://cobod.com/products/faq/

Curran, M. A. (2014). Strengths and Limitations of Life Cycle Assessment. In *Background and Future Prospects in Life Cycle Assessment* (pp. 189-206).

Dabaieh, M., Heinonen, J., El-Mahdy, D., & Hassan, D. M. (2020). A comparative study of life cycle carbon emissions and embodied energy between sun-dried bricks and fired clay bricks. *Journal of Cleaner Production, 275*, 122998. doi:https://doi.org/10.1016/j.jclepro.2020.122998

De Schutter, G., Lesage, K., Mechtcherine, V., Nerella, V. N., Habert, G., & Agusti-Juan, I. (2018). Vision of 3D printing with concrete — Technical, economic and environmental potentials. *Cement and Concrete Research, 112*, 25-36. doi:https://doi.org/10.1016/j.cemconres.2018.06.001

Du, Q., Bao, T., Li, Y., Huang, Y., & Shao, L. (2019). Impact of prefabrication technology on the cradle-to-site CO2 emissions of residential buildings. *Clean Technologies and Environmental Policy, 21*(7), 1499-1514. doi:10.1007/s10098-019-01723-y

ecoinvent Database. (2022). Retrieved from https://ecoinvent.org/the-ecoinvent-database/

El-Sayegh, S., Romdhane, L., & Manjikian, S. (2020). A critical review of 3D printing in construction: benefits, challenges, and risks. *Archives of Civil and Mechanical Engineering, 20*(2), 34. doi:10.1007/s43452-020-00038-w

Gosselin, C., Duballet, R., Roux, P., Gaudillière, N., Dirrenberger, J., & Morel, P. (2016). Large-scale 3D printing of ultra-high performance concrete – a new processing route for architects and builders. *Materials & Design, 100,* 102-109. doi:https://doi.org/10.1016/j.matdes.2016.03.097

Holt, C., Edwards, L., Keyte, L., Moghaddam, F., & Townsend, B. (2019). Chapter 17 - Construction 3D Printing. In J. G. Sanjayan, A. Nazari, & B. Nematollahi (Eds.), *3D Concrete Printing Technology* (pp. 349-370): Butterworth-Heinemann.

Homeless World Cup Foundation. (2020). Global homelessness statistics. Retrieved from https://homelessworldcup.org/homelessness-statistics/

Hossain, M. A., Zhumabekova, A., Paul, S. C., & Kim, J. R. (2020). A Review of 3D Printing in Construction and its Impact on the Labor Market. *Sustainability, 12*(20), 8492. Retrieved from https://www.mdpi.com/2071-1050/12/20/8492

Huang, B., Chen, Y., McDowall, W., Türkeli, S., Bleischwitz, R., & Geng, Y. (2019). Embodied GHG emissions of building materials in Shanghai. *Journal of Cleaner Production, 210,* 777-785. doi:https://doi.org/10.1016/j.jclepro.2018.11.030

Huijbregts, M. A. J., Steinmann, Z. J. N., Elshout, P. M. F., Stam, G., Verones, F., Vieira, M., et al. (2017). ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. *The International Journal of Life Cycle Assessment, 22*(2), 138-147. doi:10.1007/s11367-016-1246-y

IEA. (2019). *Global Status Report for Buildings and Construction 2019*. Retrieved from Paris: https://www.iea.org/reports/global-status-report-for-buildings-and-construction-2019

Khan, M. A. (2020). Mix suitable for concrete 3D printing: A review. *Materials Today: Proceedings, 32*, 831-837. doi:https://doi.org/10.1016/j.matpr.2020.03.825

Khasreen, M. M., Banfill, P. F. G., & Menzies, G. F. (2009). Life-Cycle Assessment and the Environmental Impact of Buildings: A Review. *Sustainability, 1*(3), 674-701. Retrieved from https://www.mdpi.com/2071-1050/1/3/674

Leibniz Institute of Ecological Urban and Regional Development, & Data, I. P. f. S. (2022). Multi-family house 1991 to 2010. Retrieved from http://ioer-bdat.de/en/structural-data/domestic-buildings/mfh-1991-2010/

Leibniz Institute of Ecological Urban and Regional Development, & Information Portal for Structural Data. (2022). One- and two-family house from 1991 to 2010. Retrieved from http://ioer-bdat.de/en/structural-data/domestic-buildings/otfh-1991-2010/

Li, H., Luo, Z., Xu, X., Cang, Y., & Yang, L. (2021). Assessing the embodied carbon reduction potential of straw bale rural houses by hybrid life cycle assessment: A four-case study. *Journal of Cleaner Production, 303*, 127002. doi:https://doi.org/10.1016/j.jclepro.2021.127002

Liaw, C.-Y., & Guvendiren, M. (2017). Current and emerging applications of 3D printing in medicine. *Biofabrication, 9*(2), 024102. doi:10.1088/1758-5090/aa7279

Lowke, D., Dini, E., Perrot, A., Weger, D., Gehlen, C., & Dillenburger, B. (2018). Particle-bed 3D printing in concrete construction – Possibilities and challenges. *Cement and Concrete Research, 112*, 50-65. doi:https://doi.org/10.1016/j.cemconres.2018.05.018

Lutkevich, B., & Kakade, S. (2022). Bill of materials (BOM). Retrieved from https://www.techtarget.com/searcherp/definition/bill-of-materials-BoM

Millington, K. A. (2017). *How changes in technology and automation will affect the labour market in Africa*. Retrieved from https://opendocs.ids.ac.uk/opendocs/bitstream/handle/20.500.12413/13054/K4D_HDR_Impact%20of%20automation%20on%20jobs%20in%20Africa.pdf?sequence=166&isAllowed=y

Mohan, M. K., Rahul, A. V., De Schutter, G., & Van Tittelboom, K. (2021). Extrusion-based concrete 3D printing from a material perspective: A state-of-the-art review. *Cement and Concrete Composites, 115*, 103855. doi:https://doi.org/10.1016/j.cemconcomp.2020.103855

Morel, J. C., Mesbah, A., Oggero, M., & Walker, P. (2001). Building houses with local materials: means to drastically reduce the environmental impact of construction. *Building and Environment, 36*(10), 1119-1126. doi:https://doi.org/10.1016/S0360-1323(00)00054-8

Mosteiro-Romeroa, M., Krogmanna, U., Wallbaumb, H., Ostermeyer, Y., Senickc, J. S., & Andrews, C. J. (2014). Relative importance of electricity sources and construction practices in residential buildings: A Swiss-US comparison of energy related life-cycle impacts. *Energy and Buildings, 68*, 620-631. doi:10.1016/j.enbuild.2013.09.046

Nachal, N., Moses, J. A., Karthik, P., & Anandharamakrishnan, C. (2019). Applications of 3D Printing in Food Processing. *Food Engineering Reviews, 11*(3), 123-141. doi:10.1007/s12393-019-09199-8

Nematollahi, B., Vijay, P., Sanjayan, J., Nazari, A., Xia, M., Naidu Nerella, V., et al. (2018). Effect of Polypropylene Fibre Addition on Properties of Geopolymers Made by 3D Printing for Digital Construction. *Materials, 11*(12), 2352. Retrieved from https://www.mdpi.com/1996-1944/11/12/2352

Novikov, F. (2014). Hidden Barriers to Construction Innovation. *Buildings Will Be Asmbld*. Retrieved from https://medium.com/buildings-will-be-asmbld/hidden-barriers-to-construction-innovation-522702de4409

Oberti, I., & Plantamura, F. (2015). Is 3D printed house sustainable?

Ortiz-Rodríguez, O., Castells, F., & Sonnemann, G. (2010). Life cycle assessment of two dwellings: One in Spain, a developed country, and one in Colombia, a country under development. *Science of the Total Environment, 408*, 2435-2443. doi:10.1016/j.scitotenv.2010.02.021

PRé Sustainability, & Various Authors. (2020). SimaPro database manual - Methods library. In: PRé Sustainability.

Pullen, S. F. (2000). Energy used in the Construction and Operation of Houses. *Architectural Science Review, 43*(2), 87-94. doi:10.1080/00038628.2000.9697439

Ramya, A., & Vanapalli , S. I. (2016). 3D Pritning Technologies in Various Applications. *International Journal of Mechanical Engineering and Technology (IJMET), 7*(3), 396-409. Retrieved from http://www.iaeme.com/IJMET/issues.asp?JType=IJMET&VType=7&IType=3

Renzulli, P. A., Notarnicola, B., Tassielli, G., Arcese, G., & Di Capua, R. (2016). Life Cycle Assessment of Steel Produced in an Italian Integrated Steel Mill. *Sustainability, 8*(8), 719. Retrieved from https://www.mdpi.com/2071-1050/8/8/719

Ringen, K., Seegal, J., & Englund, A. (1995). Safety and health in the construction industry. *Annual review of public health, 16*, 165-188. doi:10.1146/annurev.pu.16.050195.001121

Rolfe, S., Garnham, L., Godwin, J., Anderson, I., Seaman, P., & Donaldson, C. (2020). Housing as a social determinant of health and wellbeing: developing an empirically-informed realist theoretical framework. *BMC Public Health, 20*(1), 1138. doi:10.1186/s12889-020-09224-0

Salzer, C., Wallbaum, H., Ostermeyer, Y., & Kono, J. (2017). Environmental performance of social housing in emerging economies: life cycle assessment of conventional and alternative construction methods in the Philippines. *The International Journal of Life Cycle Assessment, 22*(11), 1785-1801. doi:10.1007/s11367-017-1362-3

Shahrubudin, N., Lee, T. C., & Ramlan, R. (2019). An Overview on 3D Printing Technology: Technological, Materials, and Applications. *Procedia Manufacturing, 35*, 1286-1296. doi:https://doi.org/10.1016/j.promfg.2019.06.089

Siddika, A., Mamun, M. A. A., Ferdous, W., Saha, A. K., & Alyousef, R. (2020). 3D-printed concrete: applications, performance, and challenges. *Journal of Sustainable Cement-Based Materials, 9*(3), 127-164. doi:10.1080/21650373.2019.1705199

Tay, Y. W. D., Panda, B., Paul, S. C., Noor Mohamed, N. A., Tan, M. J., & Leong, K. F. (2017). 3D printing trends in building and construction industry: a review. *Virtual and Physical Prototyping, 12*(3), 261-276. doi:10.1080/17452759.2017.1326724

Truitt, P. (2009). Potential for reducing greenhouse gas emissions in the construction sector. *US Environmental Protection Agency*, 12.

UN. Secretary-General. (2021). *Progress towards the Sustainable Development Goals: report of the Secretary-General*. Retrieved from New York: https://unstats.un.org/sdgs/report/2019/goal-11

United Nations. (2015). *Transforming Our World: The 2030 Agenda for Sustainable Development*. Retrieved from New York:

United Nations. (2022). SDG 11. Retrieved from https://sdgs.un.org/goals/goal11

United Nations Environment Programme. (2021). *2021 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector*. Retrieved from Nairobi:

Vanderploeg, A., Lee, S.-E., & Mamp, M. (2017). The application of 3D printing technology in the fashion industry. *International Journal of Fashion Design, Technology and Education, 10*(2), 170-179. doi:10.1080/17543266.2016.1223355

Venkatesh, K., Kasun, H., & Rehan, S. (2015). Life Cycle Assesment of Residential Buildings: A Case Study in Canada. *Zenodo*. doi:https://doi.org/10.5281/zenodo.1107700

WASP. (2022). La prima Casa Stampata in 3D generata con la Tera | Gaia. Retrieved from https://www.3dwasp.com/casa-stampata-in-3d-gaia/

Weng, Y., Li, M., Ruan, S., Wong, T. N., Tan, M. J., Ow Yeong, K. L., et al. (2020). Comparative economic, environmental and productivity assessment of a concrete bathroom unit fabricated through 3D printing and a precast approach. *Journal of Cleaner Production, 261*, 121245. doi:https://doi.org/10.1016/j.jclepro.2020.121245

World Health Organization. (2018). *WHO Housing and heakth guidelines*. Retrieved from Geneva: https://apps.who.int/iris/bitstream/handle/10665/276001/9789241550376-eng.pdf

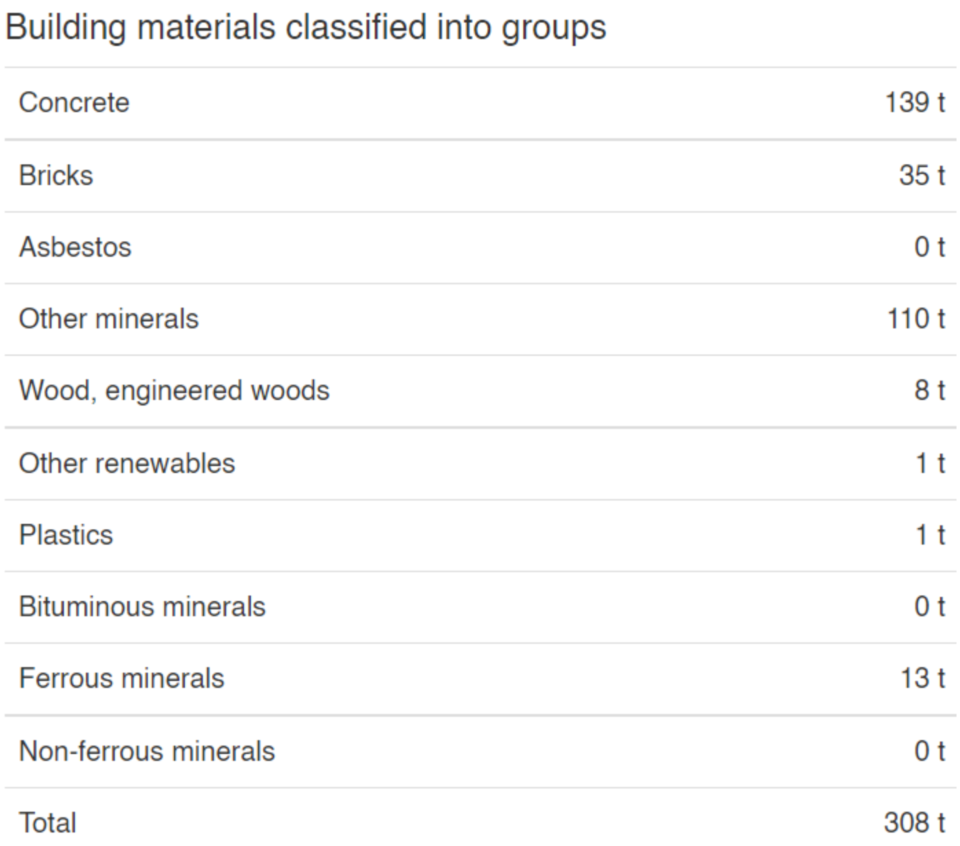
Zhang, W., Tan, S., Lei, Y., & Wang, S. (2014). Life cycle assessment of a single-family residential building in Canada: A case study. *Building Simulation, 7*(4), 429-438. doi:10.1007/s12273-013-0159-y

Supplementary information

Bills of materials

Germany 1

Figure SI1. Pictures of typical one- or two- family houses built in Germany between 1991 and 2010 (Leibniz Institute of Ecological Urban and Regional Development et al., 2022)



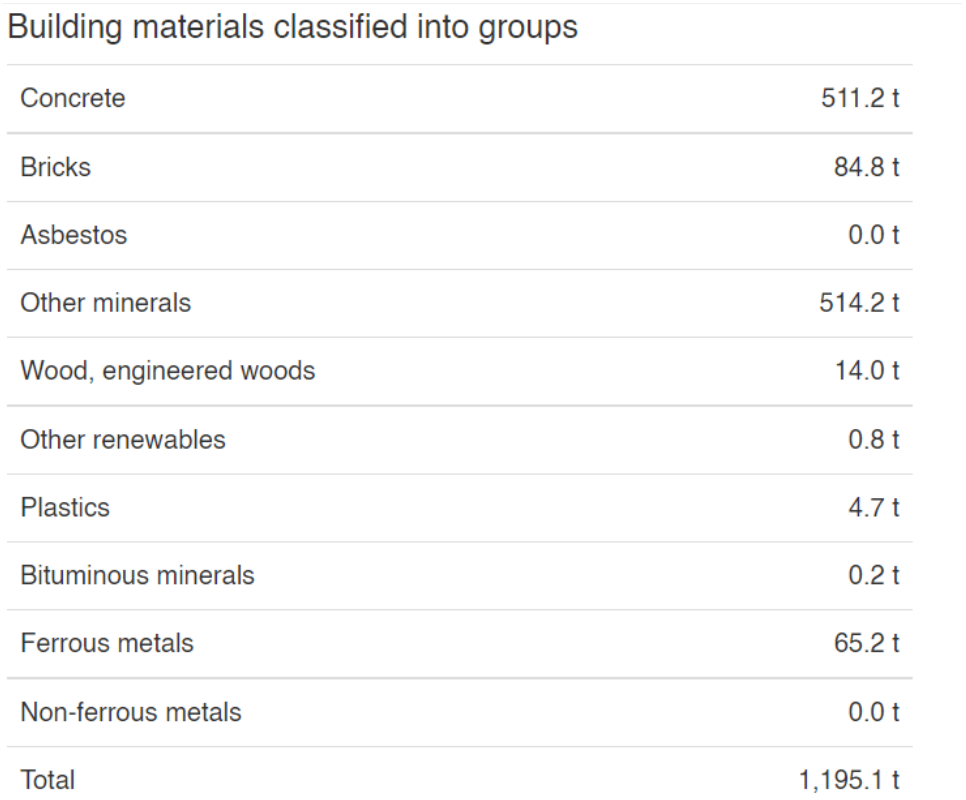
Building materials classified into groups

Concrete	139 t
Bricks	35 t
Asbestos	0 t
Other minerals	110 t
Wood, engineered woods	8 t
Other renewables	1 t
Plastics	1 t
Bituminous minerals	0 t
Ferrous minerals	13 t
Non-ferrous minerals	0 t
Total	308 t

Figure SI2. List of materials used to build a typical one- or two- family houses in Germany between 1991 and 2010 (Leibniz Institute of Ecological Urban and Regional Development et al., 2022).

Germany 2

Figure SI3. Pictures of typical multi-family houses built in Germany between 1991 and 2010 (Leibniz Institute of Ecological Urban and Regional Development et al., 2022).

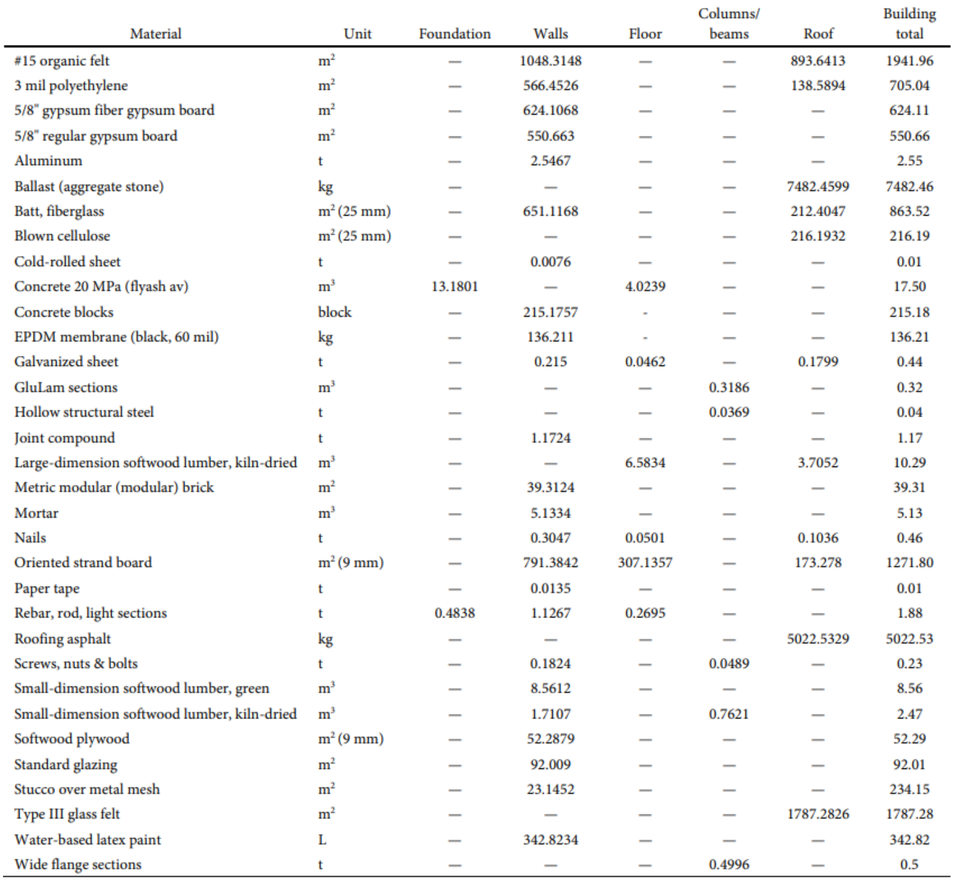


Building materials classified into groups

Concrete	511.2 t
Bricks	84.8 t
Asbestos	0.0 t
Other minerals	514.2 t
Wood, engineered woods	14.0 t
Other renewables	0.8 t
Plastics	4.7 t
Bituminous minerals	0.2 t
Ferrous metals	65.2 t
Non-ferrous metals	0.0 t
Total	1,195.1 t

Figure SI4. List of materials typically used to build multi-family houses in Germany between 1991 and 2010 (Leibniz Institute of Ecological Urban and Regional Development et al., 2022).

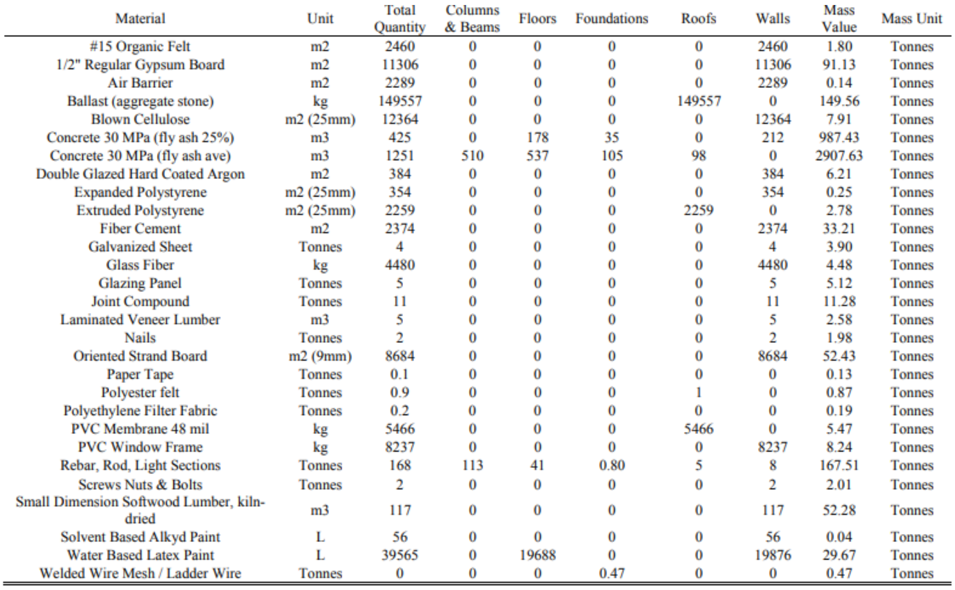
Canada 1



Material	Unit	Foundation	Walls	Floor	Columns/ beams	Roof	Building total
#15 organic felt	m^2	—	1048.3148	—	—	893.6413	1941.96
3 mil polyethylene	m^2	—	566.4526	—	—	138.5894	705.04
5/8" gypsum fiber gypsum board	m^2	—	624.1068	—	—	—	624.11
5/8" regular gypsum board	m^2	—	550.663	—	—	—	550.66
Aluminum	t	—	2.5467	—	—	—	2.55
Ballast (aggregate stone)	kg	—	—	—	—	7482.4599	7482.46
Batt, fiberglass	m^2 (25 mm)	—	651.1168	—	—	212.4047	863.52
Blown cellulose	m^2 (25 mm)	—	—	—	—	216.1932	216.19
Cold-rolled sheet	t	—	0.0076	—	—	—	0.01
Concrete 20 MPa (flyash av)	m^3	13.1801	—	4.0239	—	—	17.50
Concrete blocks	block	—	215.1757	-	—	—	215.18
EPDM membrane (black, 60 mil)	kg	—	136.211	-	—	—	136.21
Galvanized sheet	t	—	0.215	0.0462	—	0.1799	0.44
GluLam sections	m^3	—	—	—	0.3186	—	0.32
Hollow structural steel	t	—	—	—	0.0369	—	0.04
Joint compound	t	—	1.1724	—	—	—	1.17
Large-dimension softwood lumber, kiln-dried	m^3	—	—	6.5834	—	3.7052	10.29
Metric modular (modular) brick	m^2	—	39.3124	—	—	—	39.31
Mortar	m^3	—	5.1334	—	—	—	5.13
Nails	t	—	0.3047	0.0501	—	0.1036	0.46
Oriented strand board	m^2 (9 mm)	—	791.3842	307.1357	—	173.278	1271.80
Paper tape	t	—	0.0135	—	—	—	0.01
Rebar, rod, light sections	t	0.4838	1.1267	0.2695	—	—	1.88
Roofing asphalt	kg	—	—	—	—	5022.5329	5022.53
Screws, nuts & bolts	t	—	0.1824	—	0.0489	—	0.23
Small-dimension softwood lumber, green	m^3	—	8.5612	—	—	—	8.56
Small-dimension softwood lumber, kiln-dried	m^3	—	1.7107	—	0.7621	—	2.47
Softwood plywood	m^2 (9 mm)	—	52.2879	—	—	—	52.29
Standard glazing	m^2	—	92.009	—	—	—	92.01
Stucco over metal mesh	m^2	—	23.1452	—	—	—	234.15
Type III glass felt	m^2	—	—	—	—	1787.2826	1787.28
Water-based latex paint	L	—	342.8234	—	—	—	342.82
Wide flange sections	t	—	—	—	0.4996	—	0.5

Figure SI5. Bill of material used to build the house Canada 1 (Zhang et al., 2014).

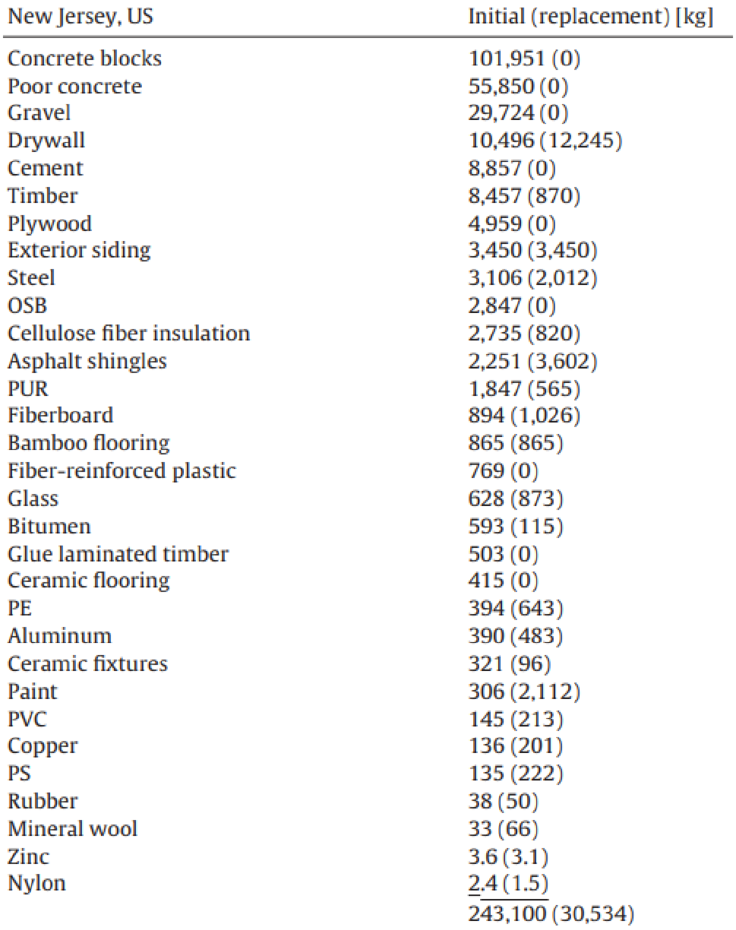
Canada 2



Material	Unit	Total Quantity	Columns & Beams	Floors	Foundations	Roofs	Walls	Mass Value	Mass Unit
#15 Organic Felt	m2	2460	0	0	0	0	2460	1.80	Tonnes
1/2" Regular Gypsum Board	m2	11306	0	0	0	0	11306	91.13	Tonnes
Air Barrier	m2	2289	0	0	0	0	2289	0.14	Tonnes
Ballast (aggregate stone)	kg	149557	0	0	0	149557	0	149.56	Tonnes
Blown Cellulose	m2 (25mm)	12364	0	0	0	0	12364	7.91	Tonnes
Concrete 30 MPa (fly ash 25%)	m3	425	0	178	35	0	212	987.43	Tonnes
Concrete 30 MPa (fly ash ave)	m3	1251	510	537	105	98	0	2907.63	Tonnes
Double Glazed Hard Coated Argon	m2	384	0	0	0	0	384	6.21	Tonnes
Expanded Polystyrene	m2 (25mm)	354	0	0	0	0	354	0.25	Tonnes
Extruded Polystyrene	m2 (25mm)	2259	0	0	0	2259	0	2.78	Tonnes
Fiber Cement	m2	2374	0	0	0	0	2374	33.21	Tonnes
Galvanized Sheet	Tonnes	4	0	0	0	0	4	3.90	Tonnes
Glass Fiber	kg	4480	0	0	0	0	4480	4.48	Tonnes
Glazing Panel	Tonnes	5	0	0	0	0	5	5.12	Tonnes
Joint Compound	Tonnes	11	0	0	0	0	11	11.28	Tonnes
Laminated Veneer Lumber	m3	5	0	0	0	0	5	2.58	Tonnes
Nails	Tonnes	2	0	0	0	0	2	1.98	Tonnes
Oriented Strand Board	m2 (9mm)	8684	0	0	0	0	8684	52.43	Tonnes
Paper Tape	Tonnes	0.1	0	0	0	0	0	0.13	Tonnes
Polyester felt	Tonnes	0.9	0	0	0	1	0	0.87	Tonnes
Polyethylene Filter Fabric	Tonnes	0.2	0	0	0	0	0	0.19	Tonnes
PVC Membrane 48 mil	kg	5466	0	0	0	5466	0	5.47	Tonnes
PVC Window Frame	kg	8237	0	0	0	0	8237	8.24	Tonnes
Rebar, Rod, Light Sections	Tonnes	168	113	41	0.80	5	8	167.51	Tonnes
Screws Nuts & Bolts	Tonnes	2	0	0	0	0	2	2.01	Tonnes
Small Dimension Softwood Lumber, kiln-dried	m3	117	0	0	0	0	117	52.28	Tonnes
Solvent Based Alkyd Paint	L	56	0	0	0	0	56	0.04	Tonnes
Water Based Latex Paint	L	39565	0	19688	0	0	19876	29.67	Tonnes
Welded Wire Mesh / Ladder Wire	Tonnes	0	0	0	0.47	0	0	0.47	Tonnes

Figure SI6. Bill of materials used in the construction of the house Canada 2 (Venkatesh et al., 2015).

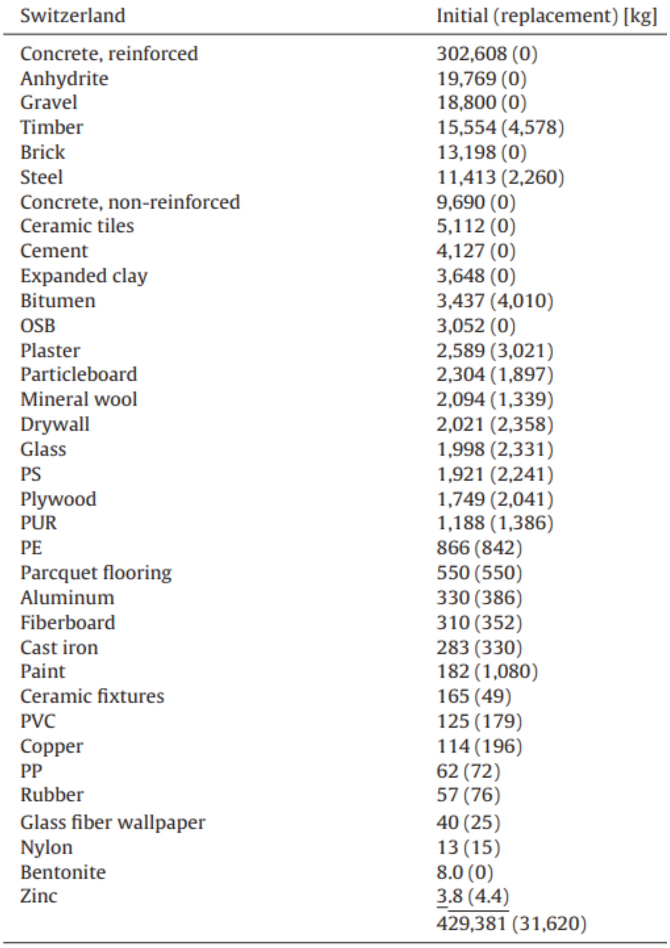
USA (New Jersey)



New Jersey, US	Initial (replacement) [kg]
Concrete blocks	101,951 (0)
Poor concrete	55,850 (0)
Gravel	29,724 (0)
Drywall	10,496 (12,245)
Cement	8,857 (0)
Timber	8,457 (870)
Plywood	4,959 (0)
Exterior siding	3,450 (3,450)
Steel	3,106 (2,012)
OSB	2,847 (0)
Cellulose fiber insulation	2,735 (820)
Asphalt shingles	2,251 (3,602)
PUR	1,847 (565)
Fiberboard	894 (1,026)
Bamboo flooring	865 (865)
Fiber-reinforced plastic	769 (0)
Glass	628 (873)
Bitumen	593 (115)
Glue laminated timber	503 (0)
Ceramic flooring	415 (0)
PE	394 (643)
Aluminum	390 (483)
Ceramic fixtures	321 (96)
Paint	306 (2,112)
PVC	145 (213)
Copper	136 (201)
PS	135 (222)
Rubber	38 (50)
Mineral wool	33 (66)
Zinc	3.6 (3.1)
Nylon	2.4 (1.5)
	243,100 (30,534)

Figure SI7. List of materials used to build the house in New Jersey (Mosteiro-Romeroa et al., 2014).

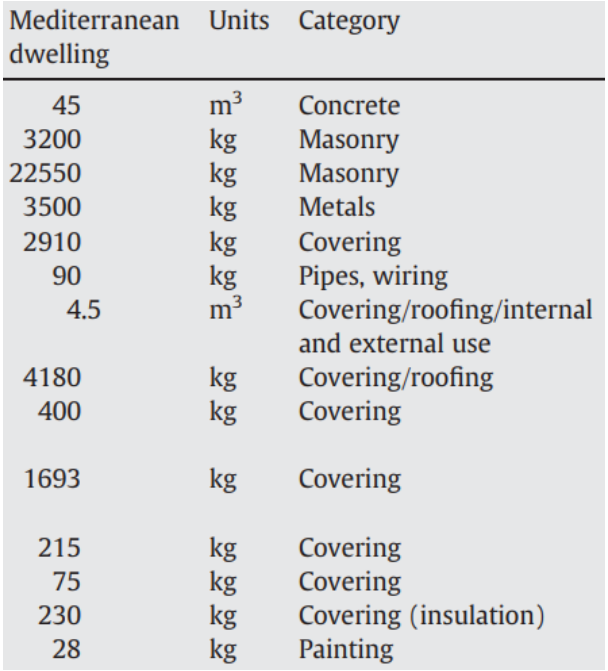
Switzerland



Switzerland	Initial (replacement) [kg]
Concrete, reinforced	302,608 (0)
Anhydrite	19,769 (0)
Gravel	18,800 (0)
Timber	15,554 (4,578)
Brick	13,198 (0)
Steel	11,413 (2,260)
Concrete, non-reinforced	9,690 (0)
Ceramic tiles	5,112 (0)
Cement	4,127 (0)
Expanded clay	3,648 (0)
Bitumen	3,437 (4,010)
OSB	3,052 (0)
Plaster	2,589 (3,021)
Particleboard	2,304 (1,897)
Mineral wool	2,094 (1,339)
Drywall	2,021 (2,358)
Glass	1,998 (2,331)
PS	1,921 (2,241)
Plywood	1,749 (2,041)
PUR	1,188 (1,386)
PE	866 (842)
Parcquet flooring	550 (550)
Aluminum	330 (386)
Fiberboard	310 (352)
Cast iron	283 (330)
Paint	182 (1,080)
Ceramic fixtures	165 (49)
PVC	125 (179)
Copper	114 (196)
PP	62 (72)
Rubber	57 (76)
Glass fiber wallpaper	40 (25)
Nylon	13 (15)
Bentonite	8.0 (0)
Zinc	3.8 (4.4)
	429,381 (31,620)

Figure SI8. List of materials used in the construction of the house in Switzerland (Mosteiro-Romeroa et al., 2014).

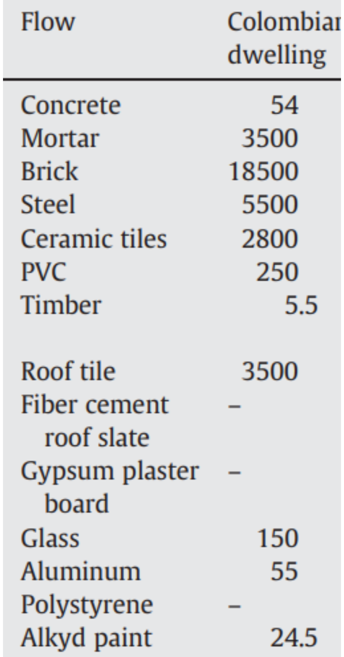
Spain



Mediterranean dwelling	Units	Category
45	m^3	Concrete
3200	kg	Masonry
22550	kg	Masonry
3500	kg	Metals
2910	kg	Covering
90	kg	Pipes, wiring
4.5	m^3	Covering/roofing/internal and external use
4180	kg	Covering/roofing
400	kg	Covering
1693	kg	Covering
215	kg	Covering
75	kg	Covering
230	kg	Covering (insulation)
28	kg	Painting

Figure SI9. List of materials used in the construction of the house in Spain (Ortiz-Rodríguez et al., 2010).

Colombia



Flow	Colombia dwelling
Concrete	54
Mortar	3500
Brick	18500
Steel	5500
Ceramic tiles	2800
PVC	250
Timber	5.5
Roof tile	3500
Fiber cement roof slate	–
Gypsum plaster board	–
Glass	150
Aluminum	55
Polystyrene	–
Alkyd paint	24.5

Figure SI10. List of materials used in the construction of the house in Colombia (Ortiz-Rodríguez et al., 2010).

Cameroon 1

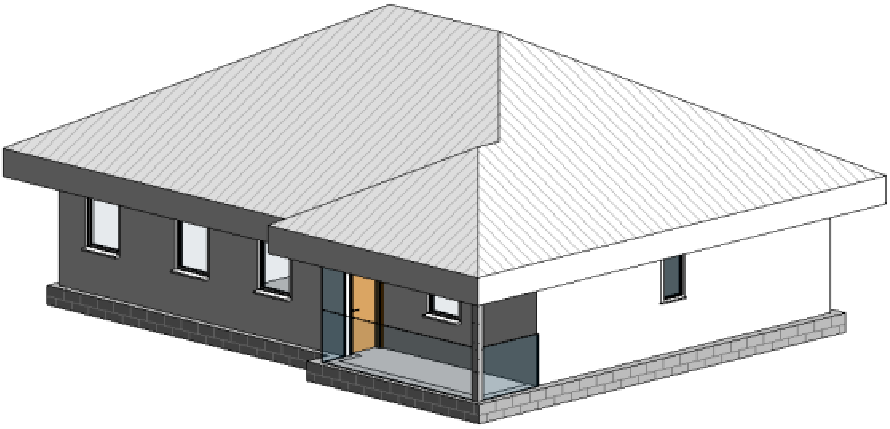
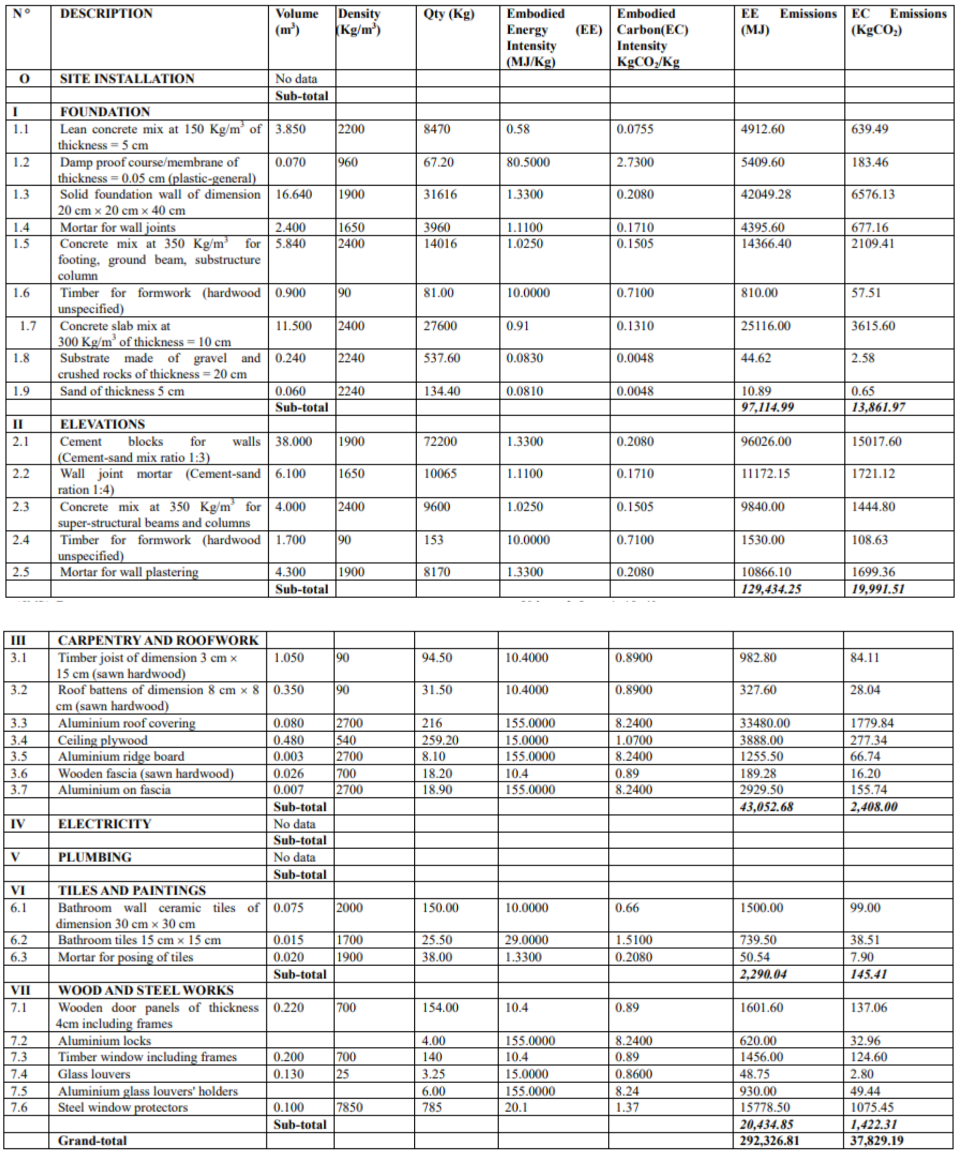


Figure SI11. 3D computer model of the cement-block house Cameroon 1 (Abanda et al., 2014).



N°	DESCRIPTION	Volume (m^3)	Density (Kg/m^3)	Qty (Kg)	Embodied Energy (EE) Intensity (MJ/Kg)	Embodied Carbon(EC) Intensity $KgCO_2/Kg$	EE Emissions (MJ)	EC Emissions ($KgCO_2$)
O	**SITE INSTALLATION**	No data						
		Sub-total						
I	**FOUNDATION**							
1.1	Lean concrete mix at 150 Kg/m^3 of thickness = 5 cm	3.850	2200	8470	0.58	0.0755	4912.60	639.49
1.2	Damp proof course/membrane of thickness = 0.05 cm (plastic-general)	0.070	960	67.20	80.5000	2.7300	5409.60	183.46
1.3	Solid foundation wall of dimension 20 cm × 20 cm × 40 cm	16.640	1900	31616	1.3300	0.2080	42049.28	6576.13
1.4	Mortar for wall joints	2.400	1650	3960	1.1100	0.1710	4395.60	677.16
1.5	Concrete mix at 350 Kg/m^3 for footing, ground beam, substructure column	5.840	2400	14016	1.0250	0.1505	14366.40	2109.41
1.6	Timber for formwork (hardwood unspecified)	0.900	90	81.00	10.0000	0.7100	810.00	57.51
1.7	Concrete slab mix at 300 Kg/m^3 of thickness = 10 cm	11.500	2400	27600	0.91	0.1310	25116.00	3615.60
1.8	Substrate made of gravel and crushed rocks of thickness = 20 cm	0.240	2240	537.60	0.0830	0.0048	44.62	2.58
1.9	Sand of thickness 5 cm	0.060	2240	134.40	0.0810	0.0048	10.89	0.65
		Sub-total					***97,114.99***	***13,861.97***
II	**ELEVATIONS**							
2.1	Cement blocks for walls (Cement-sand mix ratio 1:3)	38.000	1900	72200	1.3300	0.2080	96026.00	15017.60
2.2	Wall joint mortar (Cement-sand ration 1:4)	6.100	1650	10065	1.1100	0.1710	11172.15	1721.12
2.3	Concrete mix at 350 Kg/m^3 for super-structural beams and columns	4.000	2400	9600	1.0250	0.1505	9840.00	1444.80
2.4	Timber for formwork (hardwood unspecified)	1.700	90	153	10.0000	0.7100	1530.00	108.63
2.5	Mortar for wall plastering	4.300	1900	8170	1.3300	0.2080	10866.10	1699.36
		Sub-total					***129,434.25***	***19,991.51***
III	**CARPENTRY AND ROOFWORK**							
3.1	Timber joist of dimension 3 cm × 15 cm (sawn hardwood)	1.050	90	94.50	10.4000	0.8900	982.80	84.11
3.2	Roof battens of dimension 8 cm × 8 cm (sawn hardwood)	0.350	90	31.50	10.4000	0.8900	327.60	28.04
3.3	Aluminium roof covering	0.080	2700	216	155.0000	8.2400	33480.00	1779.84
3.4	Ceiling plywood	0.480	540	259.20	15.0000	1.0700	3888.00	277.34
3.5	Aluminium ridge board	0.003	2700	8.10	155.0000	8.2400	1255.50	66.74
3.6	Wooden fascia (sawn hardwood)	0.026	700	18.20	10.4	0.89	189.28	16.20
3.7	Aluminium on fascia	0.007	2700	18.90	155.0000	8.2400	2929.50	155.74
		Sub-total					***43,052.68***	***2,408.00***
IV	**ELECTRICITY**	No data						
		Sub-total						
V	**PLUMBING**	No data						
		Sub-total						
VI	**TILES AND PAINTINGS**							
6.1	Bathroom wall ceramic tiles of dimension 30 cm × 30 cm	0.075	2000	150.00	10.0000	0.66	1500.00	99.00
6.2	Bathroom tiles 15 cm × 15 cm	0.015	1700	25.50	29.0000	1.5100	739.50	38.51
6.3	Mortar for posing of tiles	0.020	1900	38.00	1.3300	0.2080	50.54	7.90
		Sub-total					***2,290.04***	***145.41***
VII	**WOOD AND STEEL WORKS**							
7.1	Wooden door panels of thickness 4cm including frames	0.220	700	154.00	10.4	0.89	1601.60	137.06
7.2	Aluminium locks			4.00	155.0000	8.2400	620.00	32.96
7.3	Timber window including frames	0.200	700	140	10.4	0.89	1456.00	124.60
7.4	Glass louvers	0.130	25	3.25	15.0000	0.8600	48.75	2.80
7.5	Aluminium glass louvers' holders			6.00	155.0000	8.24	930.00	49.44
7.6	Steel window protectors	0.100	7850	785	20.1	1.37	15778.50	1075.45
		Sub-total					***20,434.85***	***1,422.31***
	Grand-total						**292,326.81**	**37,829.19**

Figure SI12. Bill of materials used in the construction of the cement-block house Cameroon 1 (Abanda et al., 2014).

Cameroon 2

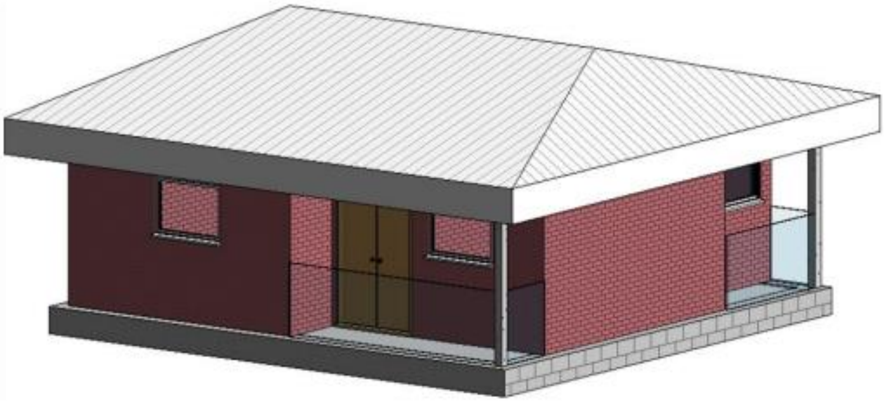
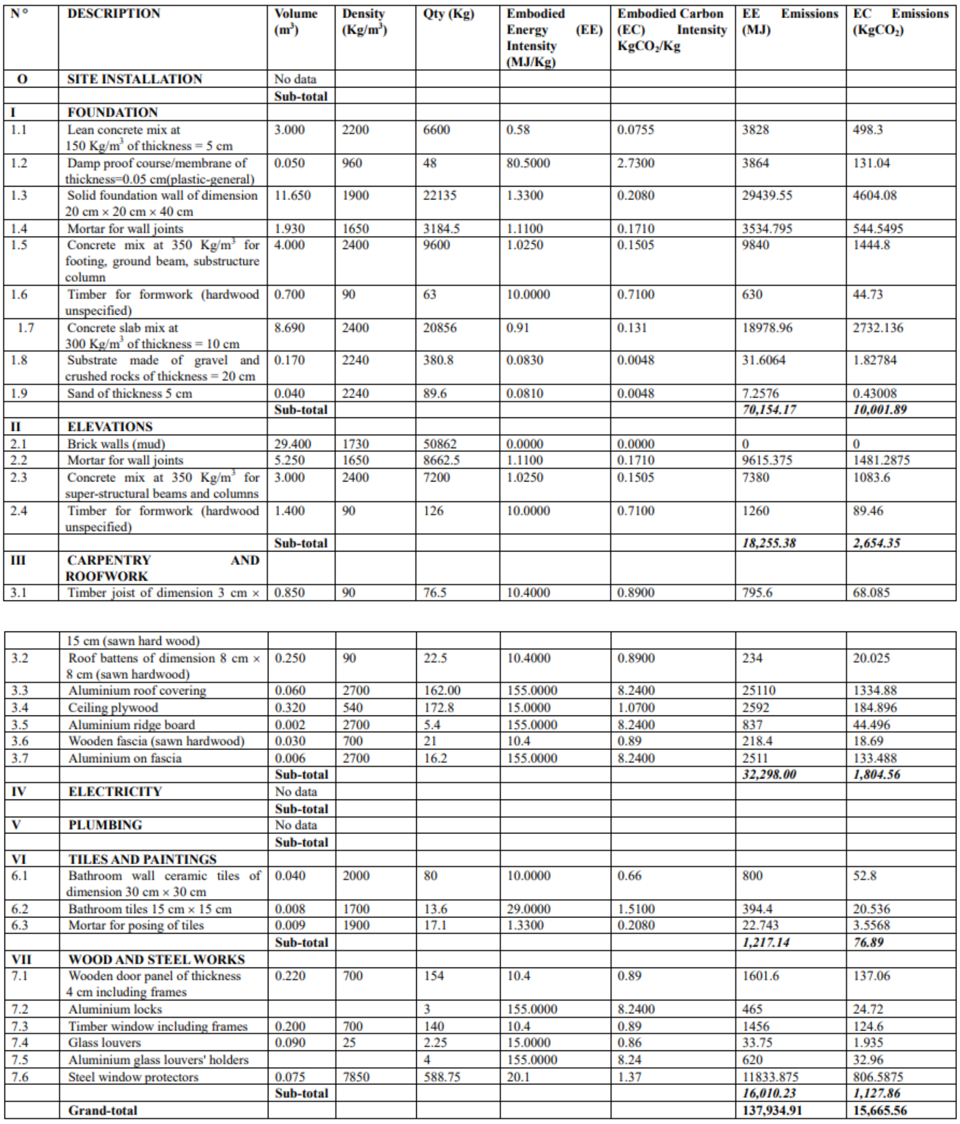


Figure SI13. 3D computer model of the mud-brick house Cameroon 2 (Abanda et al., 2014).



N°	DESCRIPTION	Volume (m^3)	Density (Kg/m^3)	Qty (Kg)	Embodied Energy (EE) Intensity (MJ/Kg)	Embodied Carbon (EC) Intensity $KgCO_2/Kg$	EE Emissions (MJ)	EC Emissions ($KgCO_2$)
O	**SITE INSTALLATION**	No data						
		Sub-total						
I	**FOUNDATION**							
1.1	Lean concrete mix at 150 Kg/m^3 of thickness = 5 cm	3.000	2200	6600	0.58	0.0755	3828	498.3
1.2	Damp proof course/membrane of thickness=0.05 cm(plastic-general)	0.050	960	48	80.5000	2.7300	3864	131.04
1.3	Solid foundation wall of dimension 20 cm × 20 cm × 40 cm	11.650	1900	22135	1.3300	0.2080	29439.55	4604.08
1.4	Mortar for wall joints	1.930	1650	3184.5	1.1100	0.1710	3534.795	544.5495
1.5	Concrete mix at 350 Kg/m^3 for footing, ground beam, substructure column	4.000	2400	9600	1.0250	0.1505	9840	1444.8
1.6	Timber for formwork (hardwood unspecified)	0.700	90	63	10.0000	0.7100	630	44.73
1.7	Concrete slab mix at 300 Kg/m^3 of thickness = 10 cm	8.690	2400	20856	0.91	0.131	18978.96	2732.136
1.8	Substrate made of gravel and crushed rocks of thickness = 20 cm	0.170	2240	380.8	0.0830	0.0048	31.6064	1.82784
1.9	Sand of thickness 5 cm	0.040	2240	89.6	0.0810	0.0048	7.2576	0.43008
		Sub-total					***70,154.17***	***10,001.89***
II	**ELEVATIONS**							
2.1	Brick walls (mud)	29.400	1730	50862	0.0000	0.0000	0	0
2.2	Mortar for wall joints	5.250	1650	8662.5	1.1100	0.1710	9615.375	1481.2875
2.3	Concrete mix at 350 Kg/m^3 for super-structural beams and columns	3.000	2400	7200	1.0250	0.1505	7380	1083.6
2.4	Timber for formwork (hardwood unspecified)	1.400	90	126	10.0000	0.7100	1260	89.46
		Sub-total					***18,255.38***	***2,654.35***
III	**CARPENTRY AND ROOFWORK**							
3.1	Timber joist of dimension 3 cm × 15 cm (sawn hard wood)	0.850	90	76.5	10.4000	0.8900	795.6	68.085
3.2	Roof battens of dimension 8 cm × 8 cm (sawn hardwood)	0.250	90	22.5	10.4000	0.8900	234	20.025
3.3	Aluminium roof covering	0.060	2700	162.00	155.0000	8.2400	25110	1334.88
3.4	Ceiling plywood	0.320	540	172.8	15.0000	1.0700	2592	184.896
3.5	Aluminium ridge board	0.002	2700	5.4	155.0000	8.2400	837	44.496
3.6	Wooden fascia (sawn hardwood)	0.030	700	21	10.4	0.89	218.4	18.69
3.7	Aluminium on fascia	0.006	2700	16.2	155.0000	8.2400	2511	133.488
		Sub-total					***32,298.00***	***1,804.56***
IV	**ELECTRICITY**	No data						
		Sub-total						
V	**PLUMBING**	No data						
		Sub-total						
VI	**TILES AND PAINTINGS**							
6.1	Bathroom wall ceramic tiles of dimension 30 cm × 30 cm	0.040	2000	80	10.0000	0.66	800	52.8
6.2	Bathroom tiles 15 cm × 15 cm	0.008	1700	13.6	29.0000	1.5100	394.4	20.536
6.3	Mortar for posing of tiles	0.009	1900	17.1	1.3300	0.2080	22.743	3.5568
		Sub-total					***1,217.14***	***76.89***
VII	**WOOD AND STEEL WORKS**							
7.1	Wooden door panel of thickness 4 cm including frames	0.220	700	154	10.4	0.89	1601.6	137.06
7.2	Aluminium locks			3	155.0000	8.2400	465	24.72
7.3	Timber window including frames	0.200	700	140	10.4	0.89	1456	124.6
7.4	Glass louvers	0.090	25	2.25	15.0000	0.86	33.75	1.935
7.5	Aluminium glass louvers' holders			4	155.0000	8.24	620	32.96
7.6	Steel window protectors	0.075	7850	588.75	20.1	1.37	11833.875	806.5875
		Sub-total					***16,010.23***	***1,127.86***
	Grand-total						**137,934.91**	**15,665.56**

Figure SI14. Bill of materials used in the construction of the mud-bricks house Cameroon 2 (Abanda et al., 2014).

Black Buffalo

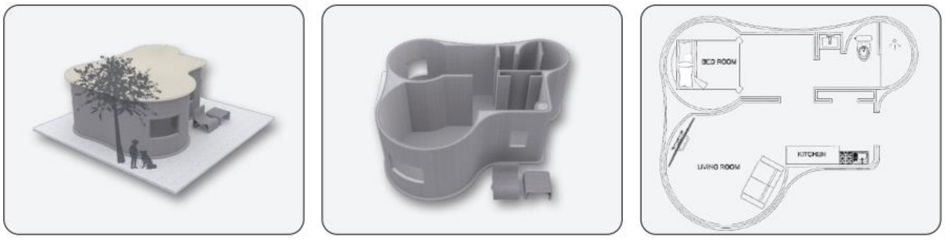


Figure SI15. Computer model of the house 3D-printed by Black Buffalo sent by the company.

Hous3Druck

Figure SI16. Picture of the house 3D-printed in Germany. Retrieved from [3D Printed House By Mense Korte Architekten & PERI 3D Construction (parametric-architecture.com)].

COBOD

Figure SI17. Picture of the house 3D-printed in Denmark by COBOD. Retrieved from Case stampate in 3D: Cobod - 3D 4Growth.

WASP

Figure SI18. Picture of the house GAIA 3D-printed by WASP in Italy. Retrieved from La prima Casa Stampata in 3D generata con la Terra | Gaia - Stampanti 3D | WASP (3dwasp.com).

Interview questions

1. According to literature, 3D printing of houses seems to be a relatively cheap and environmentally friendly way of quickly building houses; what do you think about the potential of this technology as a solution to the housing shortage in developing countries?

2. What is the current state of utilization of 3D printing for construction? And in developing countries?
3. How do you think that local economies in developing countries could benefit from the use of 3D printing?
4. The number of workers needed to build a 3D printed house is much lower than the workers needed to build homes in a conventional way. Moreover, the workers need to be more specialized. How do you think that the use of 3D printing would impact the people currently working in the construction sector? (i.e., do you think that a lot of people would lose their jobs, do you think that construction companies would invest in the formation of specialized figures, etc.?)
5. *(If you think that there is not going to be a loss of jobs, please skip this question).* People currently working as construction workers, especially in developing countries, often operate in very unsafe conditions, for very little money. The introduction of 3D printing would reduce the number of workers and result in higher salaries and safer working environments for the ones remaining. Yet, some people would find themselves unemployed. What do you think about this trade-off? (i.e., do you think that it would be a fair compromise? Why?)
6. *(If you think that there is not going to be a loss of jobs, please skip this question).* What do you think could be a solution to address the loss of jobs?
7. One of the limitations to the use of 3D printing for construction is the lack of appropriate regulations, especially in developing countries. How do you think that these legal gaps impact the structural safety of 3D-printed houses?
8. How do you think that the legal gaps impact the environmental sustainability of 3D printed houses (for example because of the lack of regulations about materials, waste management, etc.)?
9. Do you think that policymakers in developing countries will adapt fast enough to make the use of this technology feasible?
10. Would you say that there are more limitations to the applicability of 3D printing in the construction sector in developing countries? How could these limitations be addressed?
11. Do you have any additional comments you would like to add?
12. Thank you so much!! 😊