Article

Not peer-reviewed version

Impact of Building Design in BIM on the Carbon Footprint of Single-Family Houses: Life Cycle Assessment (LCA) and Case Study of Masonry and Timber Technology

Łukasz Mazur * and Anatoli Olenchuk

Posted Date: 14 September 2023

doi: 10.20944/preprints202309.0916.v1

Keywords: Carbon footprint of buildings; single-family houses; timber construction; life cycle assessment LCA; BIM

Article

Impact of Building Design in BIM on the Carbon Footprint of Single-Family Houses: Life Cycle Assessment (LCA) and Case Study of Masonry and Timber Technology

Łukasz Mazur [1,*] and Anatoli Olenchuk [2]

[1] Faculty of Engineering, Helena Chodkowska University of Technology and Economics, Jagiellońska 82f, 03-301 Warsaw, Poland; arch.lukaszmazur@gmail.com (Ł.M)
[2] Warsaw 00-001; anatolii.olenchuk@gmail.com
* Correspondence: arch.lukaszmazur@gmail.com

Abstract: Building carbon footprint analysis is a key instrument for assessing the impact of different constructions on climate change. Several standards and methodologies are available to calculate the footprint of buildings, including standards and norms, life cycle assessment (LCA), and dedicated software tools. The use of BIM software for these calculations is both scientifically justified and very practical. This scientific publication focusses on the application of a BIM-based research methodology for the analysis of the carbon footprint of a single-family house. The research process included the following steps: (i) design of a single-family house with timber frame construction using Archicad BIM software, (ii) simulation of the building energy performance using the EcoDesigner Star plug-in, (iii) life cycle assessment (LCA) using the plug-in for Archicad, (iv) preparation of a second model with traditional masonry construction for comparison, and (v) comparative analysis of the single-family house models with timber frame and masonry construction. Analysis of the results highlights significant differences in CO_2e emissions between masonry and timber buildings and the varying impact of individual elements on the total CO_2e emissions of the buildings studied. These findings are relevant for future work on sustainable building design and construction, which aims to minimise negative environmental impacts. The goal of minimising the cumulative carbon footprint of buildings is critical to achieving the Sustainable Development Goals and combating climate change.

Keywords: carbon footprint of buildings; single-family houses; timber construction; life cycle assessment LCA; BIM;

1. Introduction

Today, with increasing environmental awareness and the global need to reduce greenhouse gas (GHG) emissions, sustainable buildings are becoming a priority for the construction industry [1]. For this reason, it is possible to calculate the carbon footprint in the design of sustainable buildings, which is an important tool to assess the impact of construction on climate change [2,3].

This scientific publication is focused on the study of the carbon footprint of single-family houses. The carbon footprint includes the emissions of carbon dioxide (CO_2), methane, nitrous oxide, and other GHGs, expressed in CO_2 equivalent, emitted during the entire life cycle of a building, from the design and construction phase through operation to the end of its life. The measure of a carbon footprint is kg CO2e, a kilogram of carbon dioxide equivalent. Different greenhouse gases contribute to global warming in different ways, and the carbon dioxide equivalent allows emissions of different gases to be compared on a common scale. This allows us to compare different building solutions, whole structures and technologies, to choose the ones with the lowest CO_2 emissions. It is estimated that buildings are responsible for up to 40% of global CO_2 emissions [4,5]. The aim of the research is to understand the impact of different parts of a building's life cycle and the impact of the building's structural elements on its carbon footprint and to compare masonry and timber frame construction in terms of their impact on GHG emissions. In the context of the design and construction of residential buildings, the study of the carbon footprint becomes very important as emissions are still at a high level and the construction sector is not on a path to decarbonisation by 2050 [6]. Firstly, reducing GHG emissions is necessary to help mitigate climate change and protect the natural environment [7]. Given that the building sector is one of the main sources of these emissions, it is particularly important to adopt an environmentally friendly and sustainable approach to the design and construction of residential buildings [8,9]. Secondly, the carbon footprint study provides an opportunity to compare different design solutions in terms of their impact on GHG emissions [10]. In the case of residential buildings, the comparison between masonry and timber frame construction is particularly important, as differences in building materials and manufacturing processes can lead to significant differences in the carbon footprint. Finally, there is an economic dimension to analysing the carbon footprint of the design and construction of residential buildings [11,12]. A growing number of investors and developers are recognising that buildings with a low carbon footprint can be a source of long-term financial savings through reduced operating costs and energy consumption [13].

1.1. Building carbon footprint assessment

Several standards and methodologies have been developed to calculate the carbon footprint of buildings. The most popular methods include: (i) standards, (ii) life cycle assessment (LCA), and (iii) a dedicated computer software tool.

The assessments are based on ISO 14040 [14] and ISO 14044 [15] standards, which are the key standards for Life Cycle Assessment (LCA) and are commonly used to measure the carbon footprint of buildings and building materials [16]. The LCA method is a comprehensive research method that takes into account all stages of a building life cycle: from raw material sourcing, production, construction, exploitation, and destruction. [17,18]. The basic elements of LCA are: (1) the identification and quantitative assessment of the environmental impacts, i.e., the materials and energy consumed and the emissions and waste released into the environment; (2) the assessment of the potential impacts of these impacts; and (3) the assessment of the options available to reduce the impacts. The LCA method is widely used in the study of the carbon footprint of buildings due to its holistic approach and its consideration of many aspects of the building (**Table 1**) [19–21].

Table 1. Overview of the available LCA software.

Software	Description
OpenLCA	OpenLCA is an advanced open source software for Life Cycle Assessment (LCA) and Environmental Impact Assessment (EIA) of products and services. It has the advantage of being accessible and versatile, which makes it widely used in research and industrial practise [22].
SimaPro + Report Maker	SimaPro is a professional tool that provides a comprehensive assessment of the environmental footprint of products and processes. Report Maker is a tool that integrates with SimaPro and allows the creation of advanced reports and visualisations of the results of the LCA [23].
Tally (GaBi)	Tally is a specialised software dedicated to analysis in the construction sector, mainly in the United States [24].
Umberto LCA+	Umberto LCA+ can calculate carbon footprints, perform LCA analysis, create EPD declarations, and use the integrated ecoinvent database [25,26].

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 September 2023 doi:10.20944/preprints202309.0916.v1

One Click LCA Product Carbon & EPD Generator	One-Click LCA is an expert package that allows you to split into an LCA module and a Carbon Footprint + EPD. However, the functionality of this software is limited to calculating the carbon footprint. It is integrated with an EPD generator based on the EN15804 standard [27].

In conclusion, an analysis of five different LCA and carbon footprint calculation tools shows that there are specialised solutions on the market to meet the needs of researchers, designers, and building professionals. The variety of tools available, such as OpenLCA, SimaPro + Report Maker, Tally (GaBi), Umberto LCA+ and OneClickLCA Product Carbon & EPD Generator, allows the right choice to be made according to project specifics and user preferences. This diversity ensures that users can carry out a comprehensive analysis of the carbon footprint of buildings, which is crucial in the context of today's sustainability and environmental challenges. Whatever the specific needs and expectations, there are tools on the market that allow such analysis to be carried out professionally and efficiently. However, these tools have limited functionality for building designers - there is a need to go one step further and provide a tool to perform assessments at the design and decision stage, e.g., using BIM.

1.2. BIM in assessing the carbon footprint of buildings

The carbon footprint and life cycle assessment of buildings in the design process can be examined in the present project using Building Information Modelling (BIM) technology. BIM offers a comprehensive solution by integrating building information into a central model, creating a ‘digital twin’ of the building, which is under design. [28,29]. In the area of carbon footprint assessment, BIM software facilitates the handling of data on building materials used in project designs. These data play a crucial role in the accurate calculation of carbon emissions. It takes into account the manufacture, transport, and installation of building materials [30,31]. By using BIM software to design building elements with appropriate materials, it is possible to precisely monitor the influence of individual building design components on the entire carbon footprint of the building.

Due to increased attention in the field, there are now an increased number of tools available on the market for computing a structure's carbon footprint. The most accurate and efficient tools are those that are developed based on a high-precision 3D model of the structure, established using BIM technology. [32,33]. Integration of these tools enables users to import data from the BIM model, including building geometry, material information, and energy consumption. This feature makes it possible to perform a comprehensive carbon footprint analysis [34–36]. Using BIM software, it becomes feasible to consider all pertinent factors that impact GHG emissions throughout the life of a building. Additionally, BIM software also offers energy simulation tools to account for energy consumption during a building [37,38]. Simulations provide data on the GHG emissions related to heating, cooling and ventilation, facilitating the evaluation of a building's carbon footprint with respect to its operation. An essential benefit of BIM software is its ability to enable teamwork with different design and construction crews on a project. In this way, objective information on materials, energy consumption, and GHG emissions can be collected and updated in real-time. Technical terms are explained as necessary, and biased language is avoided. A precise and grammatically correct language variant is employed, adhering to conventional academic standards and formatting. Through ongoing data analysis, it is possible to identify the areas that have the greatest impact on carbon footprint, allowing a strategic reduction plan to be developed [39,40].

The use of BIM software to calculate the carbon footprint of buildings is not only scientifically reliable, but also pragmatic. They offer sophisticated tools for data collection, analysis, and visualisation, facilitating a deeper understanding of the impact of individual elements on carbon footprint. This enables informed design and construction decisions to minimise GHG emissions (**Table 2**).

Table 2. Overview of the available software in BIM technology.

Software	Description
One Click LCA	It is a commonly used assessment tool to measure the environmental sustainability of construction projects. One Click LCA can be added to Autodesk Revit, ArchiCAD and SketchUp as an additional feature. It enables users to perform sustainability assessments during the design process, considering factors like building materials, energy usage, and emissions.
Tally	It is an add-on to Autodesk Revit that allows you to explore the environmental impact of buildings as you design them. It allows the assessment of various aspects of sustainability, including carbon footprint, energy consumption, water consumption, materials, and waste.
eToolLCD	It is a cloud-based LCA tool that integrates with BIM software such as Revit and ArchiCAD. It allows detailed LCA analyses to be carried out, taking into account various aspects of the building, such as building materials, energy consumption, waste management, and greenhouse gas emissions.
EC3 (Embodied Carbon in Construction Calculator)	It is an LCA tool developed by the Carbon Leadership Forum. It can be an add-on to BIM software such as Revit, Rhino, and Grasshopper. It makes it easy to measure the carbon footprint of building materials, which can help designers choose sustainable materials and make informed decisions about construction.

2. Materials and Methods

This article analyses the carbon footprint of a single-family house using a BIM-based research methodology. The analysis was conducted in the following stages:

- Stage I. Designing a model for analysis, which is a single-family detached house in timber frame construction, using BIM technology (in Archicad software).
- Stage II. An energy performance simulation of the building was conducted in Archicad, using the EcoDesigner Star add-on. Through examination of the building's geometry, materials, heating and cooling systems, an energy simulation was performed to estimate the energy consumption over the life of the building (50-year period).
- Stage III. A Life Cycle Assessment (LCA) was conducted using the Archicad add-on DesignLCA [41]. A simplified approach was employed, which considered modules A1-A3 responsible for embedded emissions during the product phase, as well as module B during the use phase.

In this step, a detailed material analysis was conducted on the building materials used in the construction. ÖKOBAUDAT, a publicly available database in accordance with EN 15804+A2, was referenced for this purpose [42].

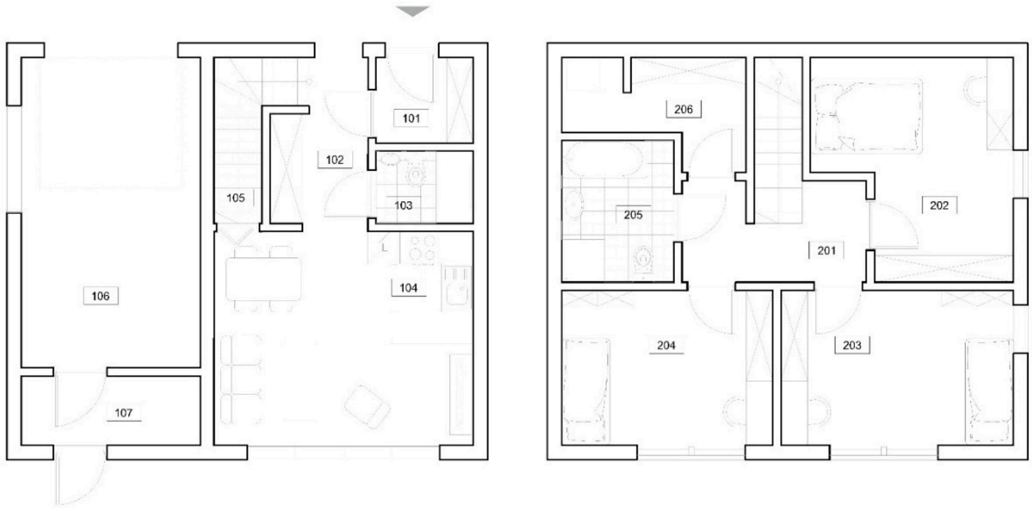
- Stage IV. A second model was analysed, constructed using traditional masonry methods. The previous stages (I-III) were repeated for this secondary model.
- Phase V. A comparative analysis of single-family building models in wood frame and masonry construction was carried out.

2.1. Analysed single-family house model

The designed building is a single-family detached house without basement. The functional program of the ground floor includes a garage, a living room with a kitchenette, a bathroom, a vestibule, and a storage room, while the first floor includes: three bedrooms with a bathroom and a laundry room. Additionally, a non-utility attic and a part of the garage are considered as space for sanitary installations (**Figure 1**). The property provides long-term housing for at least four occupants.

doi:10.20944/preprints202309.0916.v1

The rectangular structure features a symmetrical gable roof with a pitch of 40 degrees. The design evokes the archetype of a ‘modern house’ with a gabled roof and a stylish façade in understated hues (**Figure 2**).



[a] **[b]**

Figure 1. [a] Ground floor plan, description of rooms: 101 – Entrance lobby (Entry), 102 – hall, 103 – bathroom, 104 – living room with kitchen, 105 – utility room, 106 – garage, 107 – technical room. **[b]** Floor plan, description of the rooms: 201 – Landing, 202 – bedroom I, 203 – bedroom II, 204 – bedroom III, 205 – bathroom, 206 – utility room.

Figure 2. Architectural visualisation (project authors: Łukasz Mazur, Katarzyna Furgoł, Mariela Soria).

The subsequent phase of the study involved the use of BIM technology in Archicad to replicate the energy efficiency of the structure. This application enables meticulous simulation of the energy evaluation of the intended building via the built-in EcoDesigner Star add-on. The energy assessment was carried out in Warsaw (Poland), located at 16 Leżakowa Street (52°09'32.0 "N21°05’32.0 "E). Weather data from the Warsaw Okecie measuring station (52°09’46.0 "N 20°57'40.0 "E), located less than 10 km from the site, were used.

2.1.1. Building A - Masonry building

The carbon footprint of masonry construction in the context of detached houses is a complex issue, stemming from the diverse range of building materials and processes used. Specific factors do contribute to a larger carbon footprint for masonry construction. In the energy simulation of Building Model A, the primary energy sources for domestic water heating and home heating were an air source heat pump, and monocrystalline photovoltaic panels. Additional sources of energy for heating and cooling were met through electricity (**Figure 3, 4**).

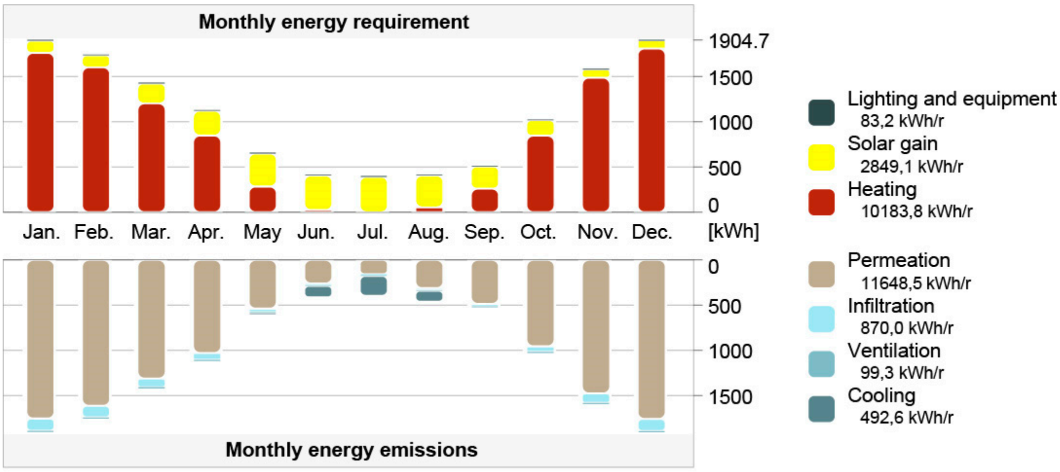


Figure 3. Energy analysis of building A in masonry construction.

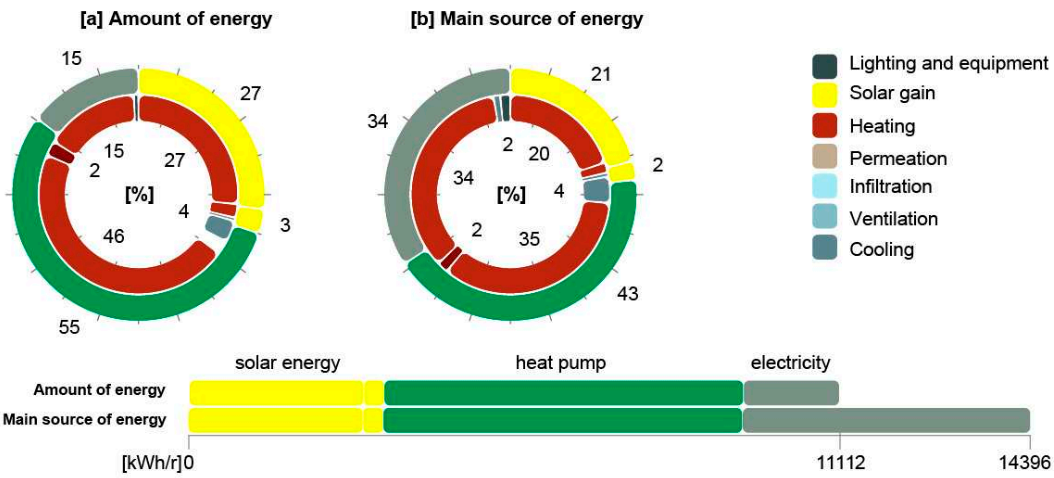


Figure 4. Energy consumption by source in building A in masonry construction: [a] amount of energy, [b] main source of energy.

Most importantly, the production of building materials used in masonry, such as cement, concrete, and bricks, is an energy-intensive process that results in significant carbon dioxide emissions. Manufacturing cement releases large amounts of greenhouse gases, so the building materials themselves can contribute to a considerable proportion of total CO_2 emissions while building a home. Furthermore, brick buildings often demand increased energy usage throughout construction stages, such as transportation, construction, and material installation. Using heavier materials when building masonry structures can increase the amount of fuel required for transportation, leading to higher GHG emissions. The carbon footprint of masonry structures is also influenced by the thermal insulation used. Masonry structures often need extra insulation for proper thermal performance. This may lead to the use of more insulation material, which comes with

 doi:10.20944/preprints202309.0916.v1

environmental costs related to manufacturing and disposal. However, it is important to mention that the advancement of novel building methods and techniques, such as using lower-emission materials during the manufacturing process, adopting renewable energy in construction procedures, and improving energy efficiency in masonry residences, may aid in decreasing the carbon footprint of single-family masonry homes. To obtain an exact calculation of the masonry constructions, it is suggested to perform a full life evaluation of the building. This includes the production of building materials, construction process, use, and dismantling. Such a study would help identify the key factors that contribute to the carbon footprint of the masonry constructions of individual houses. It would allow the suggestion of effective tactics to reduce GHG emissions.

2.1.2. Building B - Wooden building

Wooden buildings are important in the calculation of carbon footprints. Wood is a natural material that has low GHG emissions compared to conventional building materials such as concrete or steel. This is mainly because wood can store carbon dioxide during its growth period and the production of wood requires less energy compared to other materials. In the energy simulation of Building Model B, we used an air source heat pump and monocrystalline photovoltaic panels for water heating, home heating and cooling. The additional energy sources for heating and cooling are electricity (**Figures 5, 6**).

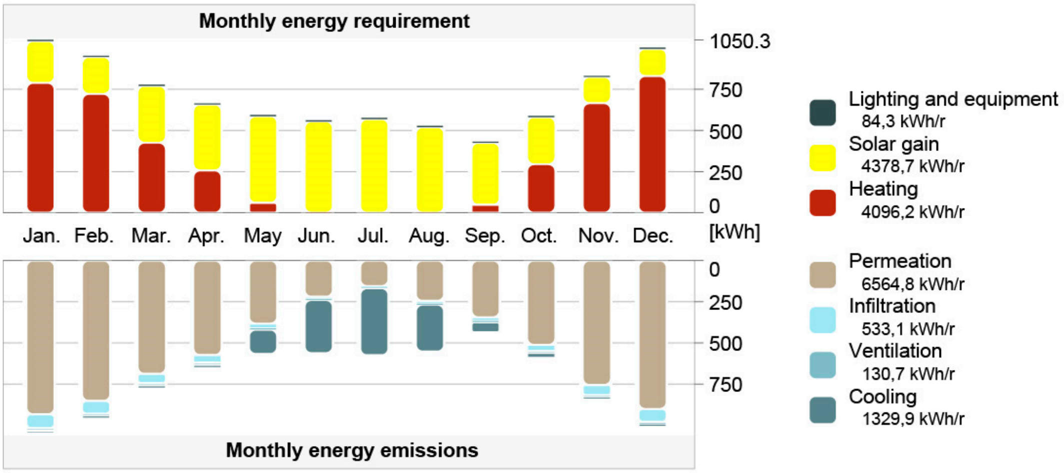


Figure 5. Energy analysis of building B in wooden construction.

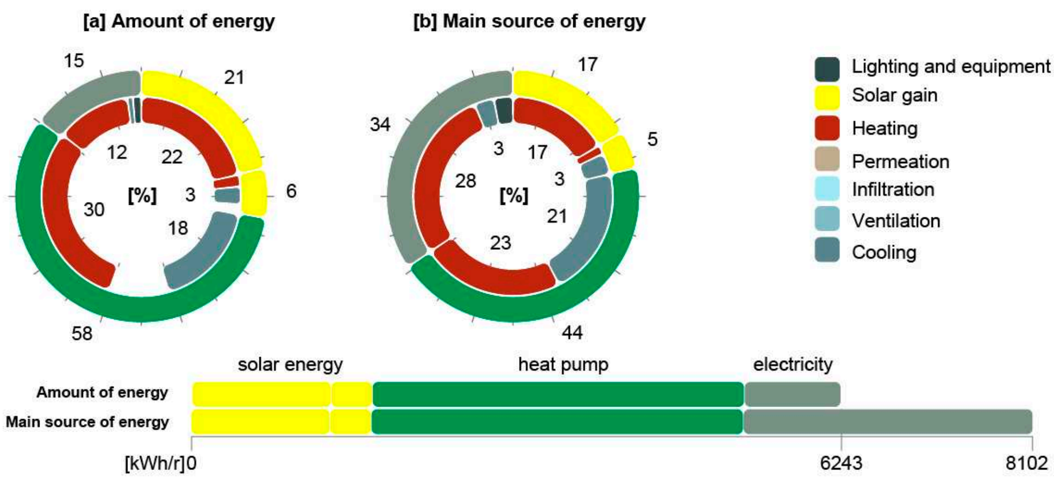


Figure 6. Energy consumption by source in building B in wooden construction: [a] amount of energy, [b] main source of energy.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 September 2023 doi:10.20944/preprints202309.0916.v1

The environmental impact of wooden buildings must consider every stage of their lifecycle, starting with timber production and including the GHG emitted from the harvesting of trees and the transport of the timber. As a building material, wood has the ability to store carbon dioxide, making its emissions lower throughout the lifecycle of the building. During the use of a wooden construction, energy usage may be reduced compared to other buildings. This is due to the insulation materials and design that limit the thermal bridges in the building. This allows for maintaining the comfort of the building temperature and reducing the energy for heating and cooling systems. This reduces the GHG emissions that come from a wooden building. However, it is important to consider other factors when analysing the carbon footprint of wooden buildings, such as the production and transport of materials used in the wooden structure, including glues and finishes. Furthermore, the assessment of GHG emissions in relation to a wooden building's life cycle should encompass the demolition and disposal stages for a precise analysis.

3. Results

3.1. Comparative analysis

A detached house energy study in masonry and wooden construction was carried out to find the level of CO_2 emissions needed to identify point B6, which is the energy use in the upcoming LCA analysis. For meaningful findings, both buildings A and B are identical models for this study (**Table 3**).

Table 3. Dimensional parameters for the building cases studied.

Parameter	Building A Masonry building	Building B Wooden building	unit
Gross floor area	153,80	139,80	m^2
Usable floor area	113,90	115,70	m^2
Number of storeys	2	2	
Number of bedrooms	3	3	units
U-value thermal conductivity coefficient [W/m²K]			
external walls	0,16	0,17	W/m^2K
roof	0,12	0,12	W/m^2K
floor on the ground	0,14	0,14	W/m^2K
Net heating energy	57,21	41,32	kWh/m^2r
Net cooling energy	5,02	12,13	kWh/m^2r
Total net energy	62,23	53,45	kWh/m^2r
Energy consumption	63,02	54,19	kWh/m^2r
Fuel consumption	9,34	9,11	kWh/m^2r
CO_2 emissions	2,02	1,97	kg/m^2r
Internal temperature (annual average value)			
heated rooms	20,66	21,51	°C
non-heated rooms	14,83	15,32	°C

3.2. LCA analysis

The LCA analysis was carried out according to the EN 15978. The authors used a simplified methodology for the product phase: A1 (extraction of raw materials), A2 (transport to the production site), A3 (production of the product), and the use phase: B6 (energy consumption). The analysis was carried out using the Archicad add-in DesignLCA. As part of our research, we analysed the emissions generated by the building materials used in both Building A (traditional brick construction) and

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 September 2023 doi:10.20944/preprints202309.0916.v1

Building B (timber frame construction). Emissions associated with building materials contribute significantly to the total carbon dioxide (CO2e) emissions from buildings. Table 4 provides a summary of the building materials used in Building A and Building B. Information on the emissivity of the materials was obtained from the public database ÖKOBAUDAT, which complies with EN 15804+A2.

Table 4. Emissions produced by construction materials used in buildings A and B.

Material	Unit	Density (kg/m3)	Embodied energy (MJ/kg) PENRT A1-3	Carbon data (kg CO2/unit)	Water m^3/m^3
Reinforcing Steel	kg	7850	5545	0,47	1,4540
Concrete C20/25	kg/m³	2400	912	178,00	0,7600
Masonry bricks	kg/m³	575	1180	113,00	0,1710
KVH cnstruction timber	kg/m³	492,92	1124	-767,80	0,2247
External silicone plaster	kg	1700	13,79	0,69	0,0219
Internal gypsum plaster	kg/m³	1000	87,27	119,40	0,2412
Steel galvanized	kg	7850	25,86	2,78	0,0031
Gypsum Fibreboard	kg/m³	1180	17,4	1,14	0,0070
Gypsum plaster board	kg/m²	10	34,85	1,62	0,0079
Swisskrono OSB	kg/m³	614,5	3950	-890,00	0,7980
Solid wood parquet	kg/m²	575	87,27	-18,74	0,0230
Aerated concrete P3	kg/m³	380	1263	184,40	0,6385
Sand	kg	1	0,03812	0,00	0,0000
Profiled aluminium sheets for roof	kg/m²	2,9	360,3	27,03	0,3715
Stoneware tiles glazed	kg/m²	20	100,4	6,18	0,0135
Stone wool aqustic insulation	kg/m³	155	1836	196,60	0,4590
Stone wool heat insulation	kg/m³	155.0	1836	196,60	0,4590
Extruded Polystyrene (XPS) foam board	kg/m³	32.7	786,5	54,24	0,3555
Air barrier membrane	kg/m²	0,1715	15,81	1,18	0,0149
PE foil dimpled	kg/m²	1,2	114,7	4,12	0,0161
Humidity variable air and vapour membrane	kg/m²	0,092	12,53	0,53	0,0035
Underroof membrane reinforced PE fabric	kg/m²	0.14	10,96	0,43	0,0037

In the case of Building B, emissions related to building materials are concentrated mainly concentrated in the production of wood and insulation materials. As a natural building material, wood has relatively low CO_2e emissions compared to other materials such as steel or concrete. In addition, the use of low-emission insulation materials helps reduce the energy used to heat and cool the building, which has a positive impact on total CO_2e emissions. In the case of Building A, emissions related to building materials are mainly in the production of cement, which is the main component of concrete. Cement production is an energy intensive process and is associated with high CO_2e emissions. Furthermore, emissions from the production of steel, which is used in the structure and load bearing elements of the building, also contribute to the total CO_2e emissions of Building A.

Based on the data in Table 2, it was possible to perform an analysis of the impact of each building element on total CO_2e emissions. As part of this study, we have broken down the impact of each element on total CO_2e expenditure, taking into account both the production phase (A1-A3) and the use phase (B6) of the building. The results of our study for each building element are presented in the following (**Table 5**).

Table 5. Impact of building elements on the distribution of total CO_2e emissions.

Construction component	Building A Masonry building		Building B Wooden building	
	[kg CO2e]	[%]	[kg CO2e]	[%]
Foundations	1045,61	3,69%	1030,86	-103,19%
External walls	9829,70	34,70%	159,75	-15,99%
Internal walls	1307,40	4,62%	-754,03	75,48%
Inter-storey floor	4076,31	14,39%	-5191,64	519,67%
Roof	1271,73	4,49%	1376,55	-137,79%
Internal installations	2575,00	9,09%	224,00	-22,42%
Stairs	2035,05	7,18%	-573,21	57,38%
Windows	5971,84	21,08%	2515,39	-251,78%
Doors	213,30	0,75%	213,30	-21,35%
Global Warming Potential - total (GWP-total)	**28325,94**	**100,00%**	**-999,03**	**100,00%**
Total emission	28325,94		5519,85	
Excess CO2 accumulation	0,00		-6518,88	

The table shows that buildings A and B differ significantly in terms of carbon dioxide emissions associated with the different construction elements. In Building A, which is a masonry building, the largest contributors to the total CO_2e emissions are the external walls (9829,70 kg CO2e),, the windows (5971,84 kg CO_2e) and the ceiling between floors (4076.31 kg CO_2e). On the other hand, in Building B, which is a timber building, the main contributors to the total CO_2e emissions are: windows (2515,39 kg CO_2e), roof (1376,55 kg CO_2e) and foundations (1030,86 kg CO_2e).

The external walls are responsible for maintaining the thermal insulation of the building, ensuring its structural stability and protecting it from the weather. In the case of Building A (masonry), the CO_2e emissions associated with this element are 9829,70 kg CO_2e, which represents up to 34,70% of the total CO_2e emissions of the building. Therefore, external walls are one of the main elements responsible for the negative environmental impact of masonry buildings. To minimise the impact of CO_2e emissions associated with external walls, it is possible to use alternative building materials with a lower environmental impact, such as materials with low CO_2 emissions during production. In addition, improved thermal insulation can reduce the amount of energy used to heat and cool the building, which will have an impact on the long-term reduction of CO_2e emissions.

The roof plays a key role in protecting the building from precipitation, wind, and other external factors. In the case of Building A (masonry), the CO_2e emissions associated with the roof are 1271,73 kg CO_2e, representing 4,49% of the total CO_2e emissions of the building. Compared to Building A, the roof of Building B generates lower CO_2e emissions due to the use of wood as a building material, which has lower CO_2e emissions compared to the traditional building materials used in Building A. Optimising the CO_2e emissions associated with the roof can include using wood from renewable sources, minimising heat loss through adequate insulation and considering energy saving technologies when using materials on the roof.

It should be noted that the CO2e emissions associated with building A are significantly higher than those of Building B. This means that masonry buildings have a greater environmental impact than timber buildings, at least as far as the analysed aspect of CO_2e emissions is concerned. However,

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 September 2023 doi:10.20944/preprints202309.0916.v1

it should be stressed that the impact of individual elements on total CO_2e emissions of the buildings is related to the use of wood, which absorbs CO_2. For example, in Building B, elements such as the ceiling (-5191,64 CO_2e), internal walls (-754,03 CO_2e) and stairs (-573,21 kg CO_2e) generate negative emissions and absorb more CO2 than they emit.

In summary, the analysis of the table shows significant differences in CO_2e emissions between masonry and wood buildings, and the differential impact of individual elements on the total CO_2e emissions of the buildings studied. These conclusions are relevant for further work on sustainable design and construction of buildings that minimise negative environmental impacts.

The cumulative energy comparison (expressed in megajoules - MJ) is an important indicator in assessing the sustainability of buildings. It allows us to compare the total energy consumption associated with different building materials and construction methods. By comparing the cumulative energy consumption of two buildings, we can obtain information on the energy efficiency of different construction approaches (**Table 6**). This highlights the importance of choosing construction materials and methods that minimise energy consumption throughout the building life cycle. Choosing energy efficient materials, exploring renewable energy sources, and implementing energy saving strategies can significantly reduce the cumulative energy consumption of buildings and promote building sustainability.

Table 6. Cumulative energy comparison [MJ].

Life cycle phase	Cumulative energy [MJ]	
	Building A Masonry building	**Building B Wooden building**
A1-A3 production stage	9 340 581,87	7 936 714,68

A comparison of the cumulative carbon footprint (expressed in kilogrammes of CO_2e) is an important indicator to evaluate the sustainability of buildings (**Table 7**). It allows us to compare the total greenhouse gas emissions associated with different building materials and construction methods. By comparing the cumulative carbon footprint of two buildings, we can obtain information on the efficiency of reducing GHG of different building materials and construction methods. This highlights the importance of choosing low-carbon materials, exploring alternatives such as recycled materials, and implementing strategies to reduce the carbon footprint throughout the lifecycle of a building.

Table 7. Cumulative carbon footprint comparison [kg CO2 e].

Life cycle phase	Carbon footprint [kg CO2 e]	
	Building A Masonry building	**Building B Wooden building**
A1-A3 production stage	28 325,94	-2 019,89
B6 energy consumption over a 50-year life cycle	17 734,35	10 326,62
Total	46 060,29	8 306,73

Comparing total water use is an important aspect in assessing the sustainability of buildings. Water is a natural resource with limited availability, so it is important to understand how much water is used by different buildings and construction methods [43,44]. Comparing the total combined water use of two buildings can provide information on the efficiency of water resources of different building materials and methods (Table 8). There is a need to develop technologies and strategies to minimise water consumption in both the production and use phases of buildings. Optimising production processes, using low-impact materials, and implementing water-saving solutions in buildings are key to achieving sustainable water use and conserving natural resources.

Table 8. Cumulative of total water consumption [m^3].

Life cycle phase	Water consumption [m^3] Building A Masonry building	Water consumption [m^3] Building B Wooden building
A1-A3 production stage	2 536,46	2 121,80

Table 9. Embodied carbon emission intensity.

House type	Net Emissions kg CO2e	Emissions Intensity kg CO2e/m2	Emissions Intensity kg CO2e/m2/yr	Emissions Intensity kg CO2e/bedroom	Energy kWh/yr
Building A – Masonry building	46 060,29	299,48	5,99	15 353,43	94,87
Building B – Wooden building	8 306,73	59,42	1,19	2 768,91	47,72

The carbon dioxide equivalent (CO_2e) is an important indicator for assessing the sustainability of buildings. It refers to the amount of carbon dioxide emitted per unit area or unit of use of a building. It measures the energy efficiency and climate change impact of the building. Comparing the intensity of CO2e of Building A and Building B allows the energy and environmental performance of different building materials and construction methods to be evaluated. It also highlights the need for further research and innovation to develop low carbon building solutions that have less impact on climate change. The drive to reduce the intensity of CO_2e emission is key to achieving sustainability and environmental protection [45].

4. Discussion

To reduce the negative environmental impact of the construction sector on the development of single-family homes, the discussion should begin with the size of the homes designed and the appropriate planning for the needs of future residents [46]. Research by Magwood and Huynh [47] shows that sensible choices at the design stage deliver the highest CO_2 reductions. Every construction project has a negative environmental impact, but by designing and implementing in a sensible and limited way, it is possible to easily reduce the negative impact. Detailed analyses of house designs by Arceo et al. [48] indicate that the elimination of only masonry basements in single-family houses can lead to an average reduction of 56% in total consumption of building materials (in terms of weight) – which significantly reducing GHG emissions from the atmosphere.

When building a single-family home, it is important to consider the needs of future occupants when analysing the space. The right design of the living space is important not only in terms of comfort and functionality, but also in terms of energy efficiency [49] and sustainable development. Regarding the project analysed (described in the publication), there is approximately 28 m^2 of living space per person for a family of 4 (2 parents and 2 children). This size is in line with the recommendations found in the literature on residential design. According to a study by Bierwirth [50], who suggested 35 m^2 per person in EU countries. Research has shown that this size is sufficient to provide a satisfactory level of comfort while minimising the environmental impact of the building by reducing the consumption of building materials and energy during operation. At the same time, the design of an optimal house footprint, i.e. one that does not unnecessarily increase the surface area, is an important element of sustainable building design. As suggested by Seo and Hwang [51], the sustainable design of single-family houses should consider both the needs of the occupants and the environmental impact of the building throughout its life cycle. In their study, the authors showed that most of the CO_2 emissions during the life cycle of a residential building are due to the operation of the building, accounting for 87-97% of the total CO_2 emissions.

Another critical aspect of creating low-carbon homes is the selection of appropriate energy-efficient building materials. It is important that these materials are not only sustainable and energy efficient, but also have the lowest possible environmental impact throughout their lifecycle, from raw material extraction, production and use to recycling or disposal [52,53]. According to Sathre and O'Connor [54], replacing non-renewable building materials such as concrete or steel with wood can lead to significant reductions in greenhouse gas emissions. The authors emphasise that wood, as a renewable material, has significant potential to store carbon, which contributes to reducing overall CO_2 emissions of a building, provided that forests are managed sustainably and wood residues are used responsibly. However, the use of wood as a building material alone does not guarantee low CO_2 emissions. As shown in a study by Polgár [55], some woods can emit more CO_2 than others, depending on the method of production, transport and processing. Therefore, it is important to consider the entire life cycle of a building material when choosing the most suitable one to build a sustainable home.

Studies carried out on masonry and timber buildings confirm that the use of renewable building materials such as wood-based materials, e.g. structural wood, OSB, significantly reduces the CO_2 emissions of the building. The use of wood frame construction for external walls reduced CO_2 emissions by almost 40%. These results are in line with the trend observed in many other building studies. According to Gustavsson et al. [56], timber frame buildings actually consume less energy and emit less CO_2 in the atmosphere compared to buildings with concrete structure buildings. The authors pointed out that wood as a building material can store carbon over the lifetime of a building, which contributes to reducing carbon dioxide emissions into the atmosphere. Werner and Richter [57], who highlighted in their study that wood as a building material has an overall favourable profile of the CO_2 emission profile throughout the LCA cycle.

Low-carbon building design should include not only the careful selection of appropriate building materials, but also a holistic energy analysis of the building's use over at least the next 50 years [58,59]. This is important because it is the energy use of a building that accounts for most of its total life cycle CO2 emissions. According to a study by Ramesh et al. [60], 80-90% of the energy consumption depends on its operation. This long-term analysis allows for the careful design and selection of appropriate energy sources. The introduction of efficient heating and cooling systems, as well as the use of renewable energy sources such as solar or wind power, can contribute significantly to reducing CO_2 emissions [61]. For example, in studies by Feist [62,63], a passive building can use up to 90% less energy for heating than a standard building. Choosing such solutions not only improves energy efficiency, but also allows for a significant reduction in usable and final energy demand [64–66].

5. Conclusions

The aim of this paper is to provide a holistic view of the carbon footprint and resource consumption in the context of single-family homes. Using advanced research tools, including Building Information Modelling (BIM) technology, a detailed analysis of individual structural elements was carried out and their impact on the whole life cycle of the building was assessed. The research process was complemented by a Life Cycle Assessment (LCA) and an Energy Performance Audit to estimate CO_2e emissions and total energy consumption over the life of the building.

The study compared two building models, one masonry and the other timber frame. By analysing the CO_2 emissions generated during both the manufacturing process (stages A1-A3) and the use of buildings (stage B), the study was able to identify the key factors influencing the carbon footprint. We confirmed that timber structures have a significantly lower carbon footprint than masonry structures, demonstrating their greater sustainability. Equally important was the comparison of total energy consumption for both types of buildings. By using the DesignLCA life cycle analysis software, we were able to accurately calculate the energy consumption (in MJ units). The results confirmed the superiority of the timber construction, which is characterised by a lower energy consumption during operation and thus has a positive impact on the environment. Aiming to minimise the cumulative carbon footprint of buildings is key to achieving sustainability goals and

 doi:10.20944/preprints202309.0916.v1

mitigating climate change. However, the research did not overlook another important natural resource - water. Although our research focused mainly on CO_2e emissions and energy consumption, the analysis of water use was an important complement to our research, highlighting that water use during construction is an important element.

As a result, this scientific publication provides valuable information and conclusions for the scientific community, design and construction professionals, and decision makers in the selection of residential building structures. The research results can contribute to the promotion of greener and more sustainable building solutions, which is extremely important in the context of climate change and environmental protection. Further research in these areas can contribute to the development of knowledge on sustainable construction and provide practical tools and guidelines for designers, investors, and decision makers to make more informed decisions on the construction of eco-efficient and energy-efficient buildings.

Author Contributions: Conceptualization, Ł.M. and A.O.; methodology, Ł.M. and A.O.; software, Ł.M. and A.O.; validation, Ł.M. and A.O.; formal analysis, Ł.M. and A.O.; investigation, , Ł.M. and A.O; resources, Ł.M. and A.O.; data curation, Ł.M. and A.O; writing—original draft preparation, Ł.M. and A.O; writing—review and editing, Ł.M. and A.O.; All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Mazur, Ł.; Bać, A.; Vaverková, M.D.; Winkler, J.; Nowysz, A.; Koda, E. Evaluation of the Quality of the Housing Environment Using Multi-Criteria Analysis That Includes Energy Efficiency: A Review. *Energies* **2022**, *15*, 7750, doi:10.3390/en15207750.
2. Shen, F.; Simayi, Z.; Yang, S.; Mamitimin, Y.; Zhang, X.; Zhang, Y. A Bibliometric Review of Household Carbon Footprint during 2000–2022. *Sustainability* **2023**, *15*, 6138, doi:10.3390/su15076138.
3. Yan, X.; Cui, S.; Xu, L.; Lin, J.; Ali, G. Carbon Footprints of Urban Residential Buildings: A Household Survey-Based Approach. *Sustainability* **2018**, *10*, 1131, doi:10.3390/su10041131.
4. Isaksson, R.; Rosvall, M.; Espuny, M.; Nunhes, T.V.; De Oliveira, O.J. How Is Building Sustainability Understood?—A Study of Research Papers and Sustainability Reports. *Sustainability* **2022**, *14*, 12430, doi:10.3390/su141912430.
5. Architecture 2030 Why the Building Sector? 2022.
6. United Nations Environment Programme *2022 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector. Nairobi.*; 2022;
7. *Buildings and Climate Change: A Summary for Decision-Makers*; UNEP DTIE, Sustainable Consumption and Production Branch: Paris, 2011; ISBN 978-92-807-3064-7.
8. Mazur, Ł. Circular Economy in Housing Architecture: Methods of Implementation. *ACTA SCIENTIARUM POLONORUM - Architectura Budownictwo* **2021**, *20*, 65–74, doi:10.22630/ASPA.2021.20.2.15.
9. Atmaca, A.; Atmaca, N. Carbon Footprint Assessment of Residential Buildings, a Review and a Case Study in Turkey. *Journal of Cleaner Production* **2022**, *340*, 130691, doi:10.1016/j.jclepro.2022.130691.
10. Sizirici, B.; Fseha, Y.; Cho, C.-S.; Yildiz, I.; Byon, Y.-J. A Review of Carbon Footprint Reduction in Construction Industry, from Design to Operation. *Materials* **2021**, *14*, 6094, doi:10.3390/ma14206094.
11. Onat, N.C.; Kucukvar, M. Carbon Footprint of Construction Industry: A Global Review and Supply Chain Analysis. *Renewable and Sustainable Energy Reviews* **2020**, *124*, 109783, doi:10.1016/j.rser.2020.109783.
12. Ahmetoğlu, S.; Tanik, A. Management of Carbon Footprint and Determination of GHG Emission Sources in Construction Sector. *International Journal of Environment and Geoinformatics* **2020**, *7*, 191–204, doi:10.30897/ijegeo.726913.
13. Starzyk, A.; Donderewicz, M.; Rybak-Niedziółka, K.; Marchwiński, J.; Grochulska-Salak, M.; Łacek, P.; Mazur, Ł.; Voronkova, I.; Vietrova, P. The Evolution of Multi-Family Housing Development Standards in the Climate Crisis: A Comparative Analysis of Selected Issues. *Buildings* **2023**, *13*, 1985, doi:10.3390/buildings13081985.
14. ISO 14040:2006 - Environmental Management -- Life Cycle Assessment -- Principles and Framewor. In.

15. ISO 14044:2006 - Environmental Management — Life Cycle Assessment — Requirements and Guidelines. In.
16. Pacheco-Torres, R.; Jadraque, E.; Roldán-Fontana, J.; Ordóñez, J. Analysis of CO2 Emissions in the Construction Phase of Single-Family Detached Houses. *Sustainable Cities and Society* **2014**, *12*, 63–68, doi:10.1016/j.scs.2014.01.003.
17. Vilches, A.; Garcia-Martinez, A.; Sanchez-Montañes, B. Life Cycle Assessment (LCA) of Building Refurbishment: A Literature Review. *Energy and Buildings* **2017**, *135*, 286–301, doi:10.1016/j.enbuild.2016.11.042.
18. Banias, G.F.; Karkanias, C.; Batsioula, M.; Melas, L.D.; Malamakis, A.E.; Geroliolios, D.; Skoutida, S.; Spiliotis, X. Environmental Assessment of Alternative Strategies for the Management of Construction and Demolition Waste: A Life Cycle Approach. *Sustainability* **2022**, *14*, 9674, doi:10.3390/su14159674.
19. Rodríguez, L.; Martínez, L.; Panameño, R.; París, O.; Muros, A.; Rodríguez, R.; Javier, R.; González, C. LCA of the NZEB El Salvador Building, a Model to Estimate the Carbon Footprint in a Tropical Country. *Journal of Cleaner Production* **2023**, *408*, 137137, doi:10.1016/j.jclepro.2023.137137.
20. Säynäjoki, A.; Heinonen, J.; Junnila, S. Carbon Footprint Assessment of a Residential Development Project. *IJESD* **2011**, 116–123, doi:10.7763/IJESD.2011.V2.107.
21. Tulevech, S.M.; Hage, D.J.; Jorgensen, S.K.; Guensler, C.L.; Himmler, R.; Gheewala, S.H. Life Cycle Assessment: A Multi-Scenario Case Study of a Low-Energy Industrial Building in Thailand. *Energy and Buildings* **2018**, *168*, 191–200, doi:10.1016/j.enbuild.2018.03.011.
22. Ciroth, A. ICT for Environment in Life Cycle Applications openLCA — A New Open Source Software for Life Cycle Assessment. *Int J Life Cycle Assess* **2007**, *12*, 209–210, doi:10.1065/lca2007.06.337.
23. How Important Is the LCA Software Tool You Choose? Comparative Results from GaBi, openLCA, SimaPro and Umberto.
24. Hemmati, M.; Messadi, T.; Gu, H. Life Cycle Assessment of Cross-Laminated Timber Transportation from Three Origin Points. *Sustainability* **2021**, *14*, 336, doi:10.3390/su14010336.
25. Luz, L.M.D.; Francisco, A.C.D.; Piekarski, C.M.; Salvador, R. Integrating Life Cycle Assessment in the Product Development Process: A Methodological Approach. *Journal of Cleaner Production* **2018**, *193*, 28–42, doi:10.1016/j.jclepro.2018.05.022.
26. Olagunju, B.D.; Olanrewaju, O.A. COMPARISON OF LIFE CYCLE ASSESSMENT TOOLS IN CEMENT PRODUCTION. *SAJIE* **2020**, *31*, doi:10.7166/31-4-2317.
27. Grossi, F.; Ge, H.; Zmeureanu, R.; Baba, F. Feasibility of Planting Trees around Buildings as a Nature-Based Solution of Carbon Sequestration—An LCA Approach Using Two Case Studies. *Buildings* **2022**, *13*, 41, doi:10.3390/buildings13010041.
28. Antón, L.Á.; Díaz, J. Integration of Life Cycle Assessment in a BIM Environment. *Procedia Engineering* **2014**, *85*, 26–32, doi:10.1016/j.proeng.2014.10.525.
29. Doan, D.T.; Ghaffarianhoseini, A.; Naismith, N.; Ghaffarianhoseini, A.; Zhang, T.; Tookey, J. Examining Green Star Certification Uptake and Its Relationship with Building Information Modelling (BIM) Adoption in New Zealand. *Journal of Environmental Management* **2019**, *250*, 109508, doi:10.1016/j.jenvman.2019.109508.
30. Potrč Obrecht, T.; Röck, M.; Hoxha, E.; Passer, A. BIM and LCA Integration: A Systematic Literature Review. *Sustainability* **2020**, *12*, 5534, doi:10.3390/su12145534.
31. Soust-Verdaguer, B.; Llatas, C.; García-Martínez, A. Critical Review of Bim-Based LCA Method to Buildings. *Energy and Buildings* **2017**, *136*, 110–120, doi:10.1016/j.enbuild.2016.12.009.
32. Röck, M.; Hollberg, A.; Habert, G.; Passer, A. LCA and BIM: Visualization of Environmental Potentials in Building Construction at Early Design Stages. *Building and Environment* **2018**, *140*, 153–161, doi:10.1016/j.buildenv.2018.05.006.
33. Carvalho, J.P.; Alecrim, I.; Bragança, L.; Mateus, R. Integrating BIM-Based LCA and Building Sustainability Assessment. *Sustainability* **2020**, *12*, 7468, doi:10.3390/su12187468.
34. Bueno, C.; Fabricio, M.M. Comparative Analysis between a Complete LCA Study and Results from a BIM-LCA Plug-In. *Automation in Construction* **2018**, *90*, 188–200, doi:10.1016/j.autcon.2018.02.028.
35. Antón, L.Á.; Díaz, J. Integration Of Lca And Bim For Sustainable Construction. **2014**, doi:10.5281/ZENODO.1092461.
36. Santos, R.; Costa, A.A.; Silvestre, J.D.; Pyl, L. Integration of LCA and LCC Analysis within a BIM-Based Environment. *Automation in Construction* **2019**, *103*, 127–149, doi:10.1016/j.autcon.2019.02.011.

37. Kim, J.B.; Jeong, W.; Clayton, M.J.; Haberl, J.S.; Yan, W. Developing a Physical BIM Library for Building Thermal Energy Simulation. *Automation in Construction* **2015**, *50*, 16–28, doi:10.1016/j.autcon.2014.10.011.
38. Kamel, E.; Memari, A.M. Review of BIM's Application in Energy Simulation: Tools, Issues, and Solutions. *Automation in Construction* **2019**, *97*, 164–180, doi:10.1016/j.autcon.2018.11.008.
39. Wei, H.; Zheng, S.; Zhao, L.; Huang, R. BIM-Based Method Calculation of Auxiliary Materials Required in Housing Construction. *Automation in Construction* **2017**, *78*, 62–82, doi:10.1016/j.autcon.2017.01.022.
40. Kim, K.P. BIM-Enabled Sustainable Housing Refurbishment—LCA Case Study. In *Sustainable Construction Technologies*; Elsevier, 2019; pp. 349–394 ISBN 978-0-12-811749-1.
41. Lendager Architects; Formfaktor Aps DesignLCA Available online: https://www.designlca.com/.
42. EN 15804+A2 - Sustainability of Construction Works - Environmental Product Declarations - Core Rules for the Product Category of Construction Products.
43. Winkler, J.; Jeznach, J.; Koda, E.; Sas, W.; Mazur, Ł.; Vaverková, M. Promoting Biodiversity: Vegetation in a Model Small Park Located in the Research and Educational Centre. *J. Ecol. Eng.* **2022**, *23*, 146–157, doi:10.12911/22998993/143997.
44. Winkler, J.; Mazur, Ł.; Smékalová, M.; Podlasek, A.; Hurajová, E.; Koda, E.; Jiroušek, M.; Jakimiuk, A.; Vaverková, M.D. Influence of Land Use on Plant Community Composition in Vysocina Region Grasslands, Czech Republic. *Environ. Protect. Eng.* **2022**, *48*, doi:10.37190/epe220402.
45. Vijayan, D.S.; Devarajan, P.; Sivasuriyan, A.; Stefańska, A.; Koda, E.; Jakimiuk, A.; Vaverková, M.D.; Winkler, J.; Duarte, C.C.; Corticos, N.D. A State of Review on Instigating Resources and Technological Sustainable Approaches in Green Construction. *Sustainability* **2023**, *15*, 6751, doi:10.3390/su15086751.
46. Magwood, C.; Bowden, E.; Javaria Ahmad; Deluca, M.; Treadaway, E.; Douglas, N. Establishing the Average Upfront Material Carbon Emissions in New Low-Rise Residential Home Construction in the City of Nelson & the City of Castlegar. **2022**, doi:10.13140/RG.2.2.16207.15527.
47. Magwood, C.; Huynh, T. *The Hidden Climate Impact of Residential Construction*; RMI, 2023;
48. Arceo, A.; Tham, M.; Guven, G.; MacLean, H.L.; Saxe, S. Capturing Variability in Material Intensity of Single-Family Dwellings: A Case Study of Toronto, Canada. *Resources, Conservation and Recycling* **2021**, *175*, 105885, doi:10.1016/j.resconrec.2021.105885.
49. Marchwiński, J.; Starzyk, A.; Kopyłow, O.; Kurtz-Orecka, K. Impact of Atrium Glazing with and without BIPV on Energy Performance of the Low-Rise Building: A Central European Case Study. *Energies* **2023**, *16*, 4683, doi:10.3390/en16124683.
50. Bierwirth, A.; Thomas, S. Estimating the Sufficiency Potential in Buildings: The Space between under Dimensioned and Oversized. *ECEEE SUMMER STUDY PROCEEDINGS* **2019**.
51. Seo, S.; Hwang, Y. Estimation of CO2 Emissions in Life Cycle of Residential Buildings. *J. Constr. Eng. Manage.* **2001**, *127*, 414–418, doi:10.1061/(ASCE)0733-9364(2001)127:5(414).
52. Moncaster, A.M.; Symons, K.E. A Method and Tool for 'Cradle to Grave' Embodied Carbon and Energy Impacts of UK Buildings in Compliance with the New TC350 Standards. *Energy and Buildings* **2013**, *66*, 514–523, doi:10.1016/j.enbuild.2013.07.046.
53. Rybak-Niedziółka, K.; Starzyk, A.; Łacek, P.; Mazur, Ł.; Myszka, I.; Stefańska, A.; Kurcjusz, M.; Nowysz, A.; Langie, K. Use of Waste Building Materials in Architecture and Urban Planning—A Review of Selected Examples. *Sustainability* **2023**, *15*, 5047, doi:10.3390/su15065047.
54. Sathre, R.; O'Connor, J. Meta-Analysis of Greenhouse Gas Displacement Factors of Wood Product Substitution. *Environmental Science & Policy* **2010**, *13*, 104–114, doi:10.1016/j.envsci.2009.12.005.
55. Polgár, A. Carbon Footprint and Sustainability Assessment of Wood Utilisation in Hungary. *Environ Dev Sustain* **2023**, doi:10.1007/s10668-023-03571-9.
56. Gustavsson, L.; Pingoud, K.; Sathre, R. Carbon Dioxide Balance of Wood Substitution: Comparing Concrete- and Wood-Framed Buildings. *Mitig Adapt Strat Glob Change* **2006**, *11*, 667–691, doi:10.1007/s11027-006-7207-1.
57. Werner, F.; Richter, K. Wooden Building Products in Comparative LCA: A Literature Review. *Int J Life Cycle Assess* **2007**, *12*, 470–479, doi:10.1065/lca2007.04.317.
58. Shao, L.; Chen, G.Q.; Chen, Z.M.; Guo, S.; Han, M.Y.; Zhang, B.; Hayat, T.; Alsaedi, A.; Ahmad, B. Systems Accounting for Energy Consumption and Carbon Emission by Building. *Communications in Nonlinear Science and Numerical Simulation* **2014**, *19*, 1859–1873, doi:10.1016/j.cnsns.2013.10.003.

 doi:10.20944/preprints202309.0916.v1

59. Kasperski, J.; Bać, A.; Oladipo, O. A Simulation of a Sustainable Plus-Energy House in Poland Equipped with a Photovoltaic Powered Seasonal Thermal Storage System. *Sustainability* **2023**, *15*, 3810, doi:10.3390/su15043810.
60. Ramesh, T.; Prakash, R.; Shukla, K.K. Life Cycle Energy Analysis of Buildings: An Overview. *Energy and Buildings* **2010**, *42*, 1592–1600, doi:10.1016/j.enbuild.2010.05.007.
61. Min, J.; Yan, G.; Abed, A.M.; Elattar, S.; Amine Khadimallah, M.; Jan, A.; Elhosiny Ali, H. The Effect of Carbon Dioxide Emissions on the Building Energy Efficiency. *Fuel* **2022**, *326*, 124842, doi:10.1016/j.fuel.2022.124842.
62. Feist, W. *Active for More Comfort: Passive House*; nternational Passive House Association: Darmstadt, 2018;
63. Peper, S.; Feist, W. *Energy Efficiency of the Passive House Standard: Expectations Confirmed by Measurements in Practice*; Passive House Institute: Darmstadt, 2015;
64. Godlewski, T.; Mazur, Ł.; Szlachetka, O.; Witowski, M.; Łukasik, S.; Koda, E. Design of Passive Building Foundations in the Polish Climatic Conditions. *Energies* **2021**, *14*, 7855, doi:10.3390/en14237855.
65. James, M.; Bill, J. *Passive House in Different Climates: The Path to Net Zero*; Routledge, Taylor & Francis Group: New York, 2016; ISBN 978-1-138-90403-3.
66. Wąs, K.; Radoń, J.; Sadłowska-Sałęga, A. Maintenance of Passive House Standard in the Light of Long-Term Study on Energy Use in a Prefabricated Lightweight Passive House in Central Europe. *Energies* **2020**, *13*, 2801, doi:10.3390/en13112801.