Life Cycle Assessment as a Major Support Tool within Multi-Criteria Design Process of Single Dwellings Located in Poland

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Abstract: Life cycle assessment is an environmental method which estimates either a process or a building material within the cradle-to-grave cycle. Presently, it is one of a few tools that include all factors which may influence the environment. The authors used this tool to prove effects connected with potential efficient energy levels and a reduction in CO₂ emissions within a building’s life cycle. For the purpose of our analyses, several types of single-family building were chosen and they were subjected to analysis in the fixed location of Warsaw. The research scope included a numerical analysis of the buildings concerning the level of embodied energies and the emission of greenhouse gases. The performed analysis proved that, within a 50-year cycle, the difference between the embodied energy from the best and worst building choices can amount to 14.87%, whereas a reduction in embodied carbon emissions can reach 20.65%. Each change in the building’s form and the type of building materials used, regardless of the usable area, influence the environmental impact. Therefore, this paper concludes that LCA, as a management tool, should be used cyclically as part of each phase of the design process. A multi-criteria method for selecting architectural solutions was proposed which considered minimum cumulative primary energy, minimum cumulative carbon emission and minimum cost of constructing a building.

Keywords: LCA; embodied energy; embodied carbon emission; life cycle assessment

1. Introduction

Despite environmental activities around the world and environmental political decisions in developed countries, we have observed a continuing increase in the impact of the construction sector on the natural environment. In 2018, the construction sector accounted for 36% (1% increase compared to 2017) of global final energy consumption and 39% of total carbon dioxide emissions (2% increase compared to 2017). A considerable share (approximately 11%) of these emissions is associated with the manufacturing of construction products such as steel, cement and glass [1]. The highest energy consumption often takes place during a building’s operation (use stage) to meet its users’ needs regarding heating, cooling, ventilation, lighting and powering appliances. However, a significant amount of energy is also consumed at earlier stages of a building’s life cycle, such as during the manufacturing of its construction products, their transport and the construction process itself. The share of embodied energy compared to the energy consumed in the operating process can be even more than 50% of the total energy over the entire life cycle of a 50-year-old building [2–5]. The share of embodied energy increases with growing energy efficiency or a reduced building life cycle [5]. In the case of low-energy or autonomous buildings, embodied energy may exceed the energy consumed for a building’s operation throughout its life cycle [6]. Improving the energy standard of a building involves an increase in the
consumption of construction materials, which increases its embodied energy (e.g., using thicker layers of thermal insulation, RES systems and systems for energy recovery from ventilation and sewage, etc.). These dependencies are presented by [7,8].

Energy efficiency may be improved only as a result of an architect’s functional and spatial decisions. For example, compact buildings without thermal bridges with glazing on the south side have a lower energy demand than buildings with an irregular wall layout and thermal bridges, as well as an unfavourable arrangement of windows [9–12].

For this reason, the role of architects in the construction process is crucial. To a large extent, they determine the elements that have an impact on a building’s aesthetics, functionality, comfort and ecology. Ecology is sometimes perceived only through the saving of energy consumed to operate a building (heating, domestic hot water lighting), but it would be more reasonable to consider all elements affecting the environment throughout a building’s life cycle. This impact occurs as early as when raw materials are obtained for the production of building materials, during construction (construction processes), operation (energy consumption), renovation and as a result of demolition. Additionally, complex interactions and processes take place all the time (e.g., transport at every stage). All of these factors cause the emission of harmful substances (e.g., greenhouse gases, dust), the consumption of energy and drinking water and the production of more or less harmful waste.

The impact of an architect’s decisions is related to the change in the use of various construction products and the applied construction processes; it also has an effect on transport and energy demand during a building’s operation. Determining the factors affecting the environment makes it possible to apply the life cycle assessment (LCA) method. This is a method for assessing a product or process throughout its life cycle, including all input and output streams, which in turn are related to the consumption of materials, energy and water, as well as harmful emissions of solid waste, gases and dust.

Due to increasingly observed changes in the climate in relation to global warming, more attention is being paid to the life-cycle carbon emission assessment (LCCO$_2$A). LCCO$_2$A is part of traditional LCA, but it focusses on embodied carbon emissions [13].

Right now, there is no single standard defining the range and limits of such analyses [13,14]. This is indicated by Y. Teng’s comparison of 173 analyses of this type developed by various authors that assumes different stages of building analysis, different life cycles and different material scopes [15]. However, for the purposes of this comparative research, these ranges are not essential, since we only examine changes in modified building models for which identical assumptions and limit values are adopted.

This paper is an attempt to specify to what extent an architect’s design-related decisions have an effect on a building’s environmental impact with respect to greenhouse gas emissions and energy consumption throughout its life cycle. The first part of this paper describes the research methods and the scope of the analysis. The next part discusses the LCA method and the scope of its analysis, as well as the database used for our research. Another element is the discussion of the climatic data used for this type of analysis. We then describe the building design principles that were applied to the models. The individual models of buildings and the differences between them are discussed. Then, the results of research regarding embodied carbon emissions and embodied energy are presented. A multi-criterion method for selecting architectural solutions is also proposed, which considers minimum greenhouse gas emissions and energy consumption. There are respective Discussion and Conclusion sections at the end of this article.
2. Materials and Methods

This study was focused on the analysis of embodied carbon emissions and embodied energy. Two calculation methods are usually used in carbon footprint analyses: (1) analysis covering only carbon dioxide emissions, or (2) the greenhouse gas emissions specified in the Kyoto Protocol (CO$_2$, CH$_4$, N$_2$O, HFCs, PFCs and SF$_6$) that take into account the impact of individual gases according to their global warming potential (GWP), as expressed in their carbon dioxide equivalent [13].

The following assumptions were made:

- Calculation method for embodied carbon emission including other greenhouse gases (GWP).
- The scope of the life cycle includes the cradle-to-gate stage (A1–A3) and the operational stage of a building whose life cycle is 20 years (B6). The scope of a cradle-to-gate analysis covers the main building components of the highest weight and volume share. LCA data (as per EN 15804) were used, and type III Environmental Product Declarations were mainly utilised as data sources.

The research consisted of the following stages:

- Analyses of the construction market in Poland were performed for single-family housing. Interviews were also conducted with 90 people. This analysis was to define popular solutions applied to single-family housing.
- The location of Warsaw was selected as the most representative place, as it is situated in the centre of the country, in climatic zone III, which covers the largest area of Poland. (Figure 1)
- A reference building design was developed according to previous market analyses. The design was made in line with the principles of designing energy-efficient buildings.
- An LCA database of construction products was created for further research. The database was regularly supplemented with information collected from other databases, type III EPDs, scientific articles and other publications. Details of the data acquisition are described in the sections: LCA Method and Database of Construction Products and Energy Carriers. The LCA database features records of initial embodied energy [MJ] and initial embodied carbon emissions [kg CO$_2$e.].
- BIM-based models of individual buildings were made in ARCHICAD (Graphisoft SE). The buildings were based on the reference building design. Descriptions of respective models can be found in the Models of Buildings section.
- Calculations of energy performance were made in accordance with Polish requirements (monthly method) using Audytor OZC (Sankom Sp. z o.o.), whereas the building designs were adjusted to the requirements of the regulation on the maximum PEF (partial maximum value of the PEF for heating, ventilation and hot water PE$_{H+W}$ for a single-family dwelling was 95 [kWh/(m$^2$ year)]) in force in Poland in 2020.
- The energy performance of buildings was calculated in the EcoDesigner Star application (dynamic hourly method).
- The dedicated Passive House Planning Package (PHPP) tool was used to verify compliance with the Passive House standard.
- Total embodied energy [MJ] and embodied carbon emissions [kg CO$_2$e.] were calculated for the building. This stage consisted of calculations made for the construction products used in the building designs (main construction products, such as components of walls, roofs, ceilings, as well as windows, doors, basic installations, i.e., gas boiler and air handling unit) and for their stage of use based on the calculations from the previous stage.
- Final conclusions were drawn.
Figure 1. Map showing the locations of 61 meteorological stations for which weather data were developed. The map shows typical meteorological years for calculating the energy performance of buildings. The selected location—Warsaw—is marked in red. Climatic zones I–V are marked on the map, as per PN-EN 12831-1:2017-08. Source: Audytor OZC.

2.1. LCA Method

LCA (life cycle assessment) is an environmental method for assessing a process or product throughout its life cycle, which is also called: cradle-to-grave. The definition in ISO 14,040 is as follows: “... compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle” [16]. It involves an analysis of potential impacts of a process or product on the natural environment.

It is currently one of the few tools that aims to include all factors that may have an environmental impact and that are related to a given product or process. The following are specified for each analysed product or process: the amount of natural resources and energy used for the production, transport or operation, and the amount of waste produced. Then, the environmental impact of these elements is assessed. The impact assessment is assigned to three damage areas: ecosystem quality, human health and resource consumption (ISO 14040:2009). This is a particularly useful tool for identifying the most adverse factors in a product’s manufacturing process to evaluate its production in the context of environmental impact.

In the case of green building design, the LCA can be utilised in two ways, as:

- A reliable source of information on individual materials and construction products at the cradle-to-gate stage—from the extraction of raw materials and product manufacturing;
- An assessment tool for the entire product (building), which can be used to optimise the reduction in adverse environmental impact.
The LCA method consists of the following phases [16]:

- Specifying the analysis purpose and scope;
- Analysis of the set of inputs and outputs—LCI (life cycle inventory), e.g., input, such as raw materials and energy, and output, such as waste;
- Life cycle impact assessment—LCIA;
- Life cycle interpretation.

To apply the LCA method in a practical environmental assessment of buildings, the key and necessary elements are databases with data (indicators of impact categories and resource consumption) on the environmental impact of individual components, materials and construction products [17].

2.2. Database of Construction Products and Energy Carriers

Information on type III EPDs was used for the purposes of developing the analysis databases. The information on type III EPDs, based on the LCA, can be applied to three scenarios:

- It includes only the product stage (A1–A3), which is called “Cradle-to-gate”;
- It includes the product stage (A1–A3) and several subsequent selected life cycle stages. Such an environmental product declaration is called “Cradle-to-gate with options”;
- It includes the full life cycle based on the full LCA, called “Cradle-to-grave”. Such an environmental product declaration covers the production, installation and use stages, including maintenance, demolition, recycling, recovery and disposal. It may also feature information module D.

The product phase (A1–A3) may include the following processes (as per EN 15804). See Table 1:

- Acquisition (e.g., extraction) and processing of raw materials, as well as the production and processing of biomass (A1);
- Reuse and recycle of products or materials from the previous system, without processes from the previous product system (A1);
- Generation of electricity and heat, including their acquisition, processing and transport (A1);
- Energy recovery and fuel recovery processes, without processes from the previous product system (A1);
- Transport to the plant boundaries (gate) and within the plant (A2);
- Production of semi-finished products and auxiliary materials (A3);
- Manufacturing of construction products (A3);
- Manufacturing of packaging (A3);
- Processing or disposal of final waste (A3).

The use of stage B6 (operational energy use) should cover the “energy use of technical building systems”, including the processing and transport of waste that results from energy consumption. Technical building systems include heating, cooling, ventilation, lighting, domestic hot water (DHW) and other systems such as security, internal transport, automation and control systems.
Table 1. Life cycle stages defined by CEN—EN 15,804 [18]. Stages A1–A3 and B6 marked in green were included in the research.

| Product Stage | Construction Process Stage | Use Stage | End of Life Stage | Info |
|---------------|----------------------------|-----------|------------------|------|
| A1 A2 A3      | A4 A5 B1 B2 B3 B4 B5 B6   | B7 C1 C2 C3 C4 D |                  |      |
| Raw material supply | Transp | Manufacturing | Transport | Construction—installation process | Use | Maintenance | Repair | Replacement | Refurbishment | Operational energy use | Deconstruction or demolition | Transport | Waste processing | Disposal | Reuse, recovery, recycling potential |

The final impact assessment in the LCA method covers several impact categories. For the purposes of this paper, which concerns the environmental assessment featuring embodied energy consumption and embodied carbon emissions related to the existence of a building, it is necessary to obtain two indicators for each material or construction product used in the design:

- Total consumption of renewable and non-renewable primary energy resources (embodied energy) expressed in MJ/kg of product;
- Global warming potential (embodied carbon emission) expressed in kg CO$_2$e/kg of product.

Assessment of other impact categories was not carried out because not all databases and data in scientific articles contain the full scope of the LCA. One such example is the ICE (Inventory of Carbon and Energy) database [19], which contains only two of the above-mentioned categories—embodied energy and embodied carbon emission.

2.3. Energy Carriers

The indicators published by the National Centre for Emissions Management—Institute of Environmental Protection—National Research Institute were used to calculate the operational carbon emission in connection with the energy carriers used during operation [20–22]. See Table 2 below.

Table 2. Indicators of pollutant emission from fuel combustion (boilers below 0.5 MW) and for electricity. s—sulphur content in milligrams per m$^3$ [Mg/m$^3$]. Source: own study based on [20–22].

| Energy Carrier or Energy | Sulphur Oxides (SO$_x$/SO$_2$) | Nitrogen Oxides (NO$_x$/NO$_2$) | Carbon Monoxide (CO) | Carbon Dioxide (CO$_2$) | Total Suspended Particles (TSP) |
|-------------------------|-------------------------------|---------------------------------|---------------------|-------------------------|--------------------------------|
| Natural gas [g/m$^3$]   | 0.002 x s                     | 1.52                            | 0.30                | 2000                    | 0.0005                         |
| Wood [g/Mg]            | 110                           | 1000                            | 26,000              | 1,200,000               | 1500                           |
| Electricity (for end users$^1$) [kg/MWh] | 1.516                         | 0.954                           | 0.234               | 798                     | 0.062                          |

$^1$ Emissions for end users include combustion systems, energy from water, energy from wind and energy from other RES, as well as the balance of exchange with foreign countries and balance losses and differences.
Table 2 is used to calculate the indicators for kWh of energy used in the building.

2.4. Climate and Weather Data

The climate has an impact on energy demand in terms of heating buildings during the heating season. Furthermore, because it can become too hot in the summer, technical solutions need to be applied to maintain proper thermal comfort inside the building.

Therefore, reliable weather data and their preparation are of importance in energy-related analyses. Weather data available for energy performance calculations are hourly average values or monthly average data. Precise calculation results are based on hourly data from hourly simulations of a building’s thermal dynamics as opposed to monthly average methods.

There is a set of standards governing the methods for determining climate data (EN ISO 15927-1, EN ISO 15927-2, EN ISO 15927-3, EN ISO 15927-4, EN ISO 15927-5). EN ISO 15927-4 specifies a method for constructing a reference year (typical meteorological year) of hourly values of appropriate meteorological data.

For the purpose of calculating the energy performance of buildings in Poland, databases for 61 meteorological stations in Poland were developed on the basis of PN-EN ISO 15927. The locations of all stations are presented in Figure 1.

Calculations performed on Audytor OZC software were made using the databases of typical meteorological years that were made available by the Ministry of Infrastructure and Construction. Averaged monthly data were used.

The EcoDesigner software can read weather data in the form of EPW (EnergyPlus Weather) files. EPW files that are available on the EnergyPlus.net website were used for further calculations; this tool and website were created by an initiative of the US Department of Energy (DOE) Building Technologies Office (BTO) and they are managed by the NREL (National Renewable Energy Laboratory). According to the EnergyPlus.net website, the EPW files were developed using the same data published by the Ministry of Infrastructure based on the data from the IMGW (observations of random hourly data confirm that they are the same as the data from files made available by the Ministry).

The current version of the Passive House Planning Package (PHPP) tool was utilised to verify whether the requirements were met for one of the building variants—the passive house standard.

PHPP uses its own weather data (source unknown), which are averaged for 6 zones set by the software authors:
- Zone I (Koszalin/Kołobrzeg);
- Zone II (Poznań/Pila);
- Zone III (Warsaw);
- Zone IV (Bialystok/Mikołajki);
- Zone V_N (Suwałki/Mikołajki);
- Zone V_S (Zakopane).

The average temperatures for individual months were compared: ISO file from the Ministry of Infrastructure, EPW file and data from PHPP for the location in Warsaw. Average temperatures are compared in Table 3 and Figure 2.

| Data Source | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 |
|-------------|----|----|----|----|----|----|----|----|----|----|----|----|
| PHPP (90)   | −3.3 | −2.1 | 1.9 | 7.7 | 14 | 16.7 | 18 | 17.3 | 13.1 | 8.2 | 3.2 | −0.9 |
| PHPP (106)  | −3.4 | −2.2 | 1.8 | 7.6 | 13 | 16.6 | 17.9 | 17.2 | 13 | 8.1 | 3.1 | −0.996 |
| MIB         | −1.2 | −0.9 | 4.4 | 6.3 | 12 | 17.1 | 19.2 | 16.6 | 12.8 | 8.2 | 2.9 | 0.8 |
| EPW STAT    | −1.2 | −0.9 | 4.4 | 6.3 | 12 | 17.1 | 19.2 | 16.6 | 12.8 | 8.2 | 2.9 | 0.8 |

1 Passive House Planning Package PHPP 2013 v. 7.1 for the default altitude of 90 m above sea level. 2 Passive House Planning Package PHPP 2013 v. 7.1 for the default altitude of 106 m above sea level—the altitude of the weather station Warszawa Okęcie. 3 Statistical data from EnergyPlus.net, compiled with the EnergyPlus Weather Converter and saved on the website in a STAT file.
2.5. Research Assumptions

2.5.1. General Assumptions

To analyse the possibilities of architectural optimisation for environmental impact, the following assumptions were made:

It was assumed that the analysis would include stages that account for more than 20% of the share of embodied energy in the entire life cycle of a building. Two life cycle stages were assumed for the research—the product stage and the use stage (Table 1), since these are the most energy-consuming stages of a building’s life cycle. The highest energy consumption and the highest emission of harmful substances are related to energy use during long-term operation of buildings and product stages (A1–A3). Together, they account for more than 92–99% of all life cycle stages (based on [23,24]). Figure 3 shows the comparison of embodied energy for various stages of a building’s life cycle. A building’s energy efficiency and life cycle duration have an impact on the proportion of energy consumption shares in the respective stages.

Figure 3. Analysis of single-family dwellings for selected life cycle stages of the building. The percentage of embodied energy for selected life cycle stages. A life cycle of 50 years was assumed for the calculations. Source: Based on [23].
Single-family dwellings, wooden structure buildings with mineral wool insulation and a straw-bale building were assumed for further analysis. One-storey and two-storey buildings were analysed, featuring buildings with a flat roof and a gable roof. Buildings with a similar usable area were designed (the smallest and largest area of 134.72 m² and 141.89 m² respectively). The research was based on our own database created on the basis of data from type III EPDs, the Oekobau.dat database and the ICE database. Two impact categories were taken into account: embodied carbon emissions and embodied energy. Digital models were prepared in ARCHICAD, while the performance calculations were made in the built-in EcoDesigner module by Strusoft. The correctness of design assumptions for a passive building was verified using PHPP. The buildings were located in Warsaw, i.e., climatic zone III (Figure 2). The carbon footprint calculations did not include the carbon dioxide capture by the trees used for the construction products (sequestration in construction products). Installations in the building were not changed, and underfloor heating supplied by a condensing gas boiler was used. Mechanical supply and exhaust ventilation with heat recovery were designed.

2.5.2. Design Rules for Energy-Efficient Buildings

The buildings were designed to meet the minimum requirements for building partitions that were in force in Poland in 2020. The buildings were designed according to best practice solutions for energy-efficient buildings. These included:

- Favourable location of the building in relation to the cardinal directions, with the bedrooms and largest rooms on the south side;
- Reduction in glazing to a minimum on the north side;
- Air tightness less than 1.5 h⁻¹ (as per the national requirements);
- Reduction in thermal bridges—non-heated vestibule (on the north side) and canopy made as an independent dilated structure;
- Ensuring that the building is compact;
- Warm and tight installation of windows in the thermal insulation layer;
- Overheating protection (canopy on the south side);
- Use of thermal storage masses;
- Mechanical supply and exhaust ventilation with recuperation.

The minimum heat transfer coefficients were assumed for the first stage, in accordance with the regulation on technical conditions (WT) (Table 4), which was in force at the time of research.

| No. | Partition              | Insulation     | Heat Transfer Coefficient [W/m² K] | Required by WT2017 [W/m² K] |
|-----|------------------------|----------------|------------------------------------|------------------------------|
| 1   | External wall          | 0.038/10 cm    | 0.22                               | 0.23                         |
| 2   | Floor on the ground    | 0.036/12 cm    | 0.26                               | 0.30                         |
| 3   | Roofs                  | 0.039/25 cm    | 0.173                              | 0.18                         |

2.5.3. Models of Buildings

Digital models of single-family dwellings were made in ARCHICAD. The building variants are summarised in Table 5.
Table 5. Summary of analysed buildings. Designations of construction technologies: A—two-storey buildings with a flat roof (ventilated roof designed as a structure made of prefabricated hollow core plates supported on external walls and internal openwork walls). The buildings differ in the solution for permanent shading of large glazings on the south side of the ground floor. Model A1 lacks a window shading solution. Model A2 features a roof, while models A3 and A4 are shaded by overhanging a section of the second floor; B—two-storey buildings with a gable roof and a ventilated flat roof. The space between the ceiling above the top floor and the roof is a non-usable area. Model B1 lacks any window shading elements. The canopy designed in model B2 is the same as in model A2, with extended eaves to partially shade the windows on the second floor. The eaves were left in model A3, but without the awning. A roof with a slope of 45° was designed for model A4, so that the loft space could be used as an attic (non-heated area); C—two-storey buildings with a usable loft with a higher knee wall; elbow windows were used for this reason. Like model A1, model C1 does not have a canopy over the windows, while an awning identical to the one in model A2 was designed for model C2 to reduce overheating; D—two-storey buildings with a usable loft. As it was necessary to adapt the usable space to the previous variants, the building was designed to be wider (by 80 cm compared to the others) on the projection, and the arrangement of its functional layout was modified. As with the previous models, a building without any canopy (D1) was made, and two models were designed with an awning. Model A3 is a building with an additional dormer; E—one-storey buildings. Buildings with twice the building area were designed, but the applied solutions were the same as in the previous models. Model E1 is based on model A2; it has a similarly structured ventilated flat roof. Model E2 was designed with a gable roof in which the wide eaves provide sunlight protection; F—buildings adapted for disabled people in wheelchairs. Model F1 is based on model B2, while model F2 is based on model E1. The buildings were slightly enlarged compared to the original ones (models F1 and F2 by 5.26 m² and 0.61 m², respectively) to meet the minimum requirements; PH—in contrast to the buildings in group A, this was built on a foundation slab. Brick walls were made of aerated concrete blocks with thicker thermal insulation (EPS $\lambda = 0.031$, 28 cm thick), and a reinforced concrete slab sloped roof with thermal insulation was constructed; WS—based on building A1/A2. The building was set on a reinforced concrete foundation slab, with wooden structure walls using 40 × 150 mm wooden posts that were spaced every 40 cm. Thermal insulation was enabled by the use of rock and glass mineral wool. Wooden beam ceilings were $h = 235$ mm; SB—based on building A1/A2. The building was set on a reinforced concrete foundation slab. Wooden structure walls using 40 × 150 mm two-branch wooden posts were spaced every 60 cm. Straw thermal insulation was attained in the walls using 45 cm thick bales. The remaining insulation used the same model as that deployed in the SZ (wooden structure) building. Wooden beam ceilings were $h = 235$ mm.

| Designation | View | Usable Heated Area [m²] | Heated Net Cubic Volume [m³] | Technology | Energy Standard (Modified Thermal Insulation Thickness) |
|-------------|------|------------------------|----------------------------|------------|-----------------------------------------------------|
| A1          | ![A1](image) | 139.85                 | 364.84                    | A          | WT2017                                              |
| A2          | ![A2](image) | 139.85                 | 364.84                    | A          | WT2017                                              |
| A3          | ![A3](image) | 139.65                 | 363.70                    | A          | WT2017                                              |
| A4          | ![A4](image) | 139.65                 | 363.70                    | A          | WT2017                                              |
| Designation | View | Usable Heated Area [m²] | Heated Net Cubic Volume [m³] | Technology | Energy Standard (Modified Thermal Insulation Thickness) |
|-------------|------|-------------------------|-------------------------------|------------|-------------------------------------------------------|
| B1          | ![B1 Diagram](image) | 139.85                  | 364.84                       | B          | WT2017                                                |
| B2          | ![B2 Diagram](image) | 139.85                  | 364.84                       | B          | WT2017                                                |
| B3          | ![B3 Diagram](image) | 139.85                  | 364.84                       | B          | WT2017                                                |
| B4          | ![B4 Diagram](image) | 139.85                  | 364.84                       | B          | WT2017                                                |
| C1          | ![C1 Diagram](image) | 134.72                  | 392.54                       | C          | WT2017                                                |
| C2          | ![C2 Diagram](image) | 134.72                  | 392.54                       | C          | WT2017                                                |
| D1          | ![D1 Diagram](image) | 139.69                  | 437.35                       | D          | WT2017                                                |
| D2          | ![D2 Diagram](image) | 139.69                  | 437.35                       | D          | WT2017                                                |
### Table 5. Cont.

| Designation | View | Usable Heated Area [m²] | Heated Net Cubic Volume [m³] | Technology | Energy Standard (Modified Thermal Insulation Thickness) |
|-------------|------|-------------------------|-----------------------------|------------|-------------------------------------------------------|
| D3          | ![Image](image1) | 141.89                  | 441.28                      | D          | WT2017                                                |
| E1          | ![Image](image2) | 140.93                  | 384.98                      | E          | WT2017                                                |
| E2          | ![Image](image3) | 140.93                  | 385.77                      | E          | WT2017                                                |
| F1          | ![Image](image4) | 144.25                  | 378.38                      | F          | WT2017                                                |
| F2          | ![Image](image5) | 141.19                  | 375.14                      | F          | WT2017                                                |
| PH          | ![Image](image6) | 139.85                  | 364.84                      | PH         | Passive House                                         |
| SZ          | ![Image](image7) | 139.80                  | 364.80                      | SZ         | No verification                                       |
| SB          | ![Image](image8) | 139.80                  | 364.80                      | SB         | No verification                                       |

A sample list of rooms in building B2 is shown in Table 6.
Table 6. List of rooms in the selected model B2/B3. Calculations in accordance with PN-ISO 9836:1997. Source: own study.

| No. | Name                        | Floor | Usable Area [m²] | Net Cubic Volume [m³] |
|-----|-----------------------------|-------|-------------------|------------------------|
| 1   | Non-heated vestibule        | I     | 2.75              | 7.19                   |
| 2   | Hall                        | I     | 10.46             | 27.25                  |
| 3   | Toilet                      | I     | 1.25              | 3.25                   |
| 4   | Technical room              | I     | 6.64              | 17.29                  |
| 5   | Living room/Kitchen         | I     | 14.71 + 30.79     | 38.32 + 80.20          |
| 6   | Study                       | I     | 5.93              | 15.44                  |
| 7   | Corridor                    | II    | 20.80             | 52.20                  |
| 8   | Bathroom                    | II    | 4.93              | 12.39                  |
| 9   | Small bathroom              | II    | 2.42              | 6.10                   |
| 10  | Room 1                      | II    | 14.36             | 36.06                  |
| 11  | Room 2                      | II    | 13.78             | 34.58                  |
| 12  | Room 3                      | II    | 13.78             | 34.58                  |
|     | TOTAL (non-heated)          |       | 139.85            | 357.65                 |
|     | TOTAL usable area           |       | 142.60            | 364.84                 |

Figures 4–6 are detailed drawings of buildings B2/B3 and the SB building.

Figure 4. Model B2, B3. Ground floor plan. Scale of 1:100. The canopy used in model B2 is marked in red. Source: own study using ARCHICAD software.
Figure 5. Model B2, B3. Floor plan. Scale of 1:100. Source: own study using ARCHICAD software.

Figure 6. Model B2, B3. Section A-A. Scale of 1:100. The canopy used in model B2 is marked in red. Source: own study using ARCHICAD software.

Ground floor plan and cross-section of the SB (straw-bale) building are shown in Figures 7–9.
Figure 7. Model A2SB. Ground floor plan. Scale of 1:100. Source: own study using ARCHICAD software.

Figure 8. Model A2SB. Floor plan. Scale of 1:100. Source: own study using ARCHICAD software.
3. Results

3.1. Results of Calculations of Energy Performance Using the Monthly Method

For the purposes of the research, calculations of the energy demand of the buildings were performed in accordance with national regulations (Regulation of the Minister of Infrastructure and Development of 27 February 2015 on the methodology for determining the energy performance of a building or part of a building and energy performance certificates) to verify that the requirements for the maximum PEF were met. The calculations were performed using Audytor OZC software. Next, the thickness of the insulation of the walls, roof and floors on the ground was increased, as none of the buildings met the requirements for the maximum PEF. After the changes, all buildings met the requirements for partitions and PEF.

3.2. Results of Calculations of Energy Performance Using the Dynamic (Hourly) Method

The building models were used for further energy performance calculations using the dynamic hourly method.

In the next step, calculations were performed for the product stage and the use stage in a 50-year cycle. Table 7 shows the results.

In the case of a longer life cycle, most energy is used during operation. Hence, high energy efficiency of buildings is important from an environmental point of view. Nonetheless we should bear in mind that, in addition to heating and ventilation, energy in residential buildings is also consumed for DHW, lighting and powering appliances. Environmental activities should therefore also be applied to other areas of energy consumption in buildings.

Based on the analyses, it may be concluded that there is a noticeable impact in terms of changes of a building’s shape on embodied energy and embodied carbon emissions. The change in technology (traditional building A2 vs. straw-bale building) resulted in a decrease in embodied energy and embodied carbon emissions by approximately 6.64% and 12.5%, respectively.

The reductions in embodied energy and embodied carbon emissions of the SB building compared to the one-storey masonry building F2 are approximately 14.87% and 20.65%, respectively.

An optimal solution is to combine all methods to reduce a building’s impact throughout its life cycle by optimising its shape, technology and energy standard.
### Table 7. Results of embodied carbon emission and embodied energy calculations for respective building models.

| Designation | CO₂ Emission—Stages: A1–A3 (Products) [kg CO₂ e.] | CO₂ Emission—B6 (Use of 1 Year) [kg CO₂ e.] | Cumulative CO₂ Emission—A1_A3 + B6 (50 Years) [Mg CO₂ e.] | Embodied Energy A1–A3 (Products) [MJ] | Operational (Primary) Energy B6, 1 Year [MJ] | Cumulative Primary Energy A1_A3 + B6 (50 Years) [GJ] | Construction Cost in EUR (8% VAT) |
|------------|-----------------------------------------------|-----------------------------------------------|--------------------------------------------------|----------------------------------------|--------------------------------------------|-----------------------------------------------|----------------------------------|
| A1         | 59,983                                        | 3126.1                                        | 216                                              | 698,411.8                              | 56,793.924                                 | 3538                                           | 101,993                          |
| A2         | 65,851                                        | 3156.1                                        | 224                                              | 769,894.92                             | 57,447.324                                 | 3642                                           | 109,617                          |
| A3         | 63,373                                        | 3168.5                                        | 222                                              | 760,871.88                             | 57,717.396                                 | 3647                                           | 110,453                          |
| A4         | 62,076                                        | 3147.9                                        | 219                                              | 746,773.92                             | 57,268.728                                 | 3610                                           | 108,721                          |
| B1         | 60,068                                        | 3126.1                                        | 216                                              | 713,081.88                             | 56,793.924                                 | 3553                                           | 100,714                          |
| B2         | 65,943                                        | 3163.3                                        | 224                                              | 788,573.88                             | 57,604.14                                  | 3669                                           | 103,425                          |
| B3         | 60,076                                        | 3132.3                                        | 217                                              | 717,090.84                             | 56,928.96                                  | 3564                                           | 97,886                           |
| B4         | 60,767                                        | 3144.3                                        | 218                                              | 728,780.04                             | 57,190.32                                  | 3588                                           | 98,695                           |
| C1         | 57,297                                        | 3171.5                                        | 216                                              | 679,714.92                             | 57,782.736                                 | 3569                                           | 98,105                           |
| C2         | 63,165                                        | 3201.5                                        | 223                                              | 751,197.96                             | 58,436.136                                 | 3673                                           | 103,886                          |
| D1         | 62,856                                        | 3195.5                                        | 223                                              | 737,166.96                             | 58,305.456                                 | 3652                                           | 111,849                          |
| D2         | 68,724                                        | 3227.1                                        | 230                                              | 808,650                                | 59,993.704                                 | 3758                                           | 117,738                          |
| D3         | 71,090                                        | 3225.7                                        | 232                                              | 834,981.12                             | 59,863.212                                 | 3783                                           | 115,658                          |
| E1         | 82,259                                        | 3277.5                                        | 246                                              | 973,905.12                             | 60,991.416                                 | 3978                                           | 125,892                          |
| E2         | 71,417                                        | 3297.9                                        | 235                                              | 879,114.96                             | 60,139.332                                 | 3886                                           | 112,702                          |
| F1         | 68,994                                        | 3224.1                                        | 230                                              | 818,480.88                             | 58,928.364                                 | 3765                                           | 113,414                          |
| F2         | 83,795                                        | 3265.3                                        | 247                                              | 1,002,600                              | 59,825.7                                  | 3994                                           | 126,053                          |
| PH         | 63,333                                        | 2982.5                                        | 212                                              | 833,329                                | 53,666.316                                 | 3517                                           | 114,343                          |
| SZ         | 37,195                                        | 3299                                          | 202                                              | 510,352                                | 60,546.796                                 | 3538                                           | 131,498                          |
| SB         | 35,677                                        | 3205.5                                        | 196                                              | 474,038                                | 58,523.256                                 | 3400                                           | 105,541                          |
| min.       |                                               |                                               | 196                                              |                                       |                                           | 3400                                           | 97,886                           |

### 3.3. Selection of the Optimal Architectural Variant for a Single-Family Dwelling

Architects often face the problem of selecting one of many possible architectural (technical and material) solutions to ensure optimal performance based on multiple criteria. A problem defined in this way is a typical multi-criteria decision-making task. There are many methods for solving a polyoptimisation task [25–28]. The weighted sum method was chosen here, which means reducing a multi-criteria task to a single-criteria task by assigning weights to individual partial criteria. The sum of the weights should be one.

Considering the above issues, the following partial optimisation criteria were formulated:

- **Criterion I**—minimum cumulative primary energy, i.e., the sum of energy use necessary to complete the selected architectural variant of a building (E);
- **Criterion II**—minimum cumulative CO₂ emissions, i.e., the sum of carbon dioxide emissions from processes that lead to the completion of the selected architectural variant of a building (C);
- **Criterion III**—minimum cost of completion of the selected architectural variant of a building (K).

Possible architectural variants and values of partial criterion functions are defined in Table 8.

\[
F = w_1 \times E + w_2 \times C + w_3 \times K
\]  
(1)

where: \( w_1, w_2, w_3 \)—weights assigned to the respective criteria.

Since each of the partial functions (E, C, K) is defined in a different unit of measurement, i.e., in Mg CO₂ e., GJ and EUR, their values must be dimensionless to determine the minimum function as being a composite of the partial criterion functions. There are many methods to standardise the criterion function value. Standardised values were obtained here by dividing the values in each column by the highest value for a given criterion function. Weights (\( w_1, w_2, w_3 \)) for the criteria should be determined to calculate which variant is the most effective. This process has a considerable impact on the final optimisation result. The sum of all weights is always one. Five sets of weights were proposed to analyse the sensitivity of the optimal solution. The weights in the sets were selected so that respective partial criteria (E, C, K) were preferred in three sets while, in two sets, the...
weights hardly differed from each other. Their values were 0.3 or 0.4. Table 8 shows the optimisation results.

Table 8. Results of multi-criteria optimisation by weighted sum method for 5 sets of weights.

| Designation | Standardisation of CO₂ Emission | Standardisation of Cumulative Energy | Standardisation of Construction Cost | Result: Weights | Result: Weights | Result: Weights | Result: Weights |
|-------------|---------------------------------|-------------------------------------|-----------------------------------|----------------|----------------|----------------|----------------|
|             |                                 |                                     |                                   | w1 = 0.4       | w2 = 0.3       | w3 = 0.1       | w2 = 0.1       |
| A1          | 0.875                           | 0.886                               | 0.776                             | 0.849          | 0.867          | 0.797          | 0.839          |
| A2          | 0.905                           | 0.912                               | 0.834                             | 0.886          | 0.889          | 0.849          | 0.879          |
| A3          | 0.898                           | 0.913                               | 0.840                             | 0.885          | 0.894          | 0.853          | 0.879          |
| A4          | 0.888                           | 0.904                               | 0.827                             | 0.887          | 0.888          | 0.841          | 0.868          |
| B1          | 0.876                           | 0.890                               | 0.766                             | 0.847          | 0.866          | 0.789          | 0.836          |
| B2          | 0.907                           | 0.919                               | 0.787                             | 0.874          | 0.896          | 0.812          | 0.862          |
| B3          | 0.877                           | 0.892                               | 0.744                             | 0.842          | 0.865          | 0.772          | 0.829          |
| B4          | 0.882                           | 0.898                               | 0.751                             | 0.848          | 0.871          | 0.779          | 0.834          |
| C1          | 0.874                           | 0.894                               | 0.746                             | 0.841          | 0.863          | 0.774          | 0.829          |
| C2          | 0.904                           | 0.920                               | 0.790                             | 0.874          | 0.894          | 0.814          | 0.863          |
| D1          | 0.901                           | 0.915                               | 0.851                             | 0.890          | 0.897          | 0.862          | 0.885          |
| D2          | 0.931                           | 0.941                               | 0.895                             | 0.923          | 0.929          | 0.904          | 0.920          |
| D3          | 0.941                           | 0.947                               | 0.880                             | 0.924          | 0.935          | 0.892          | 0.918          |
| E1          | 0.996                           | 0.996                               | 0.957                             | 0.985          | 0.992          | 0.965          | 0.981          |
| E2          | 0.953                           | 0.973                               | 0.857                             | 0.930          | 0.945          | 0.878          | 0.921          |
| F1          | 0.932                           | 0.943                               | 0.862                             | 0.914          | 0.926          | 0.877          | 0.907          |
| F2          | 1.000                           | 1.000                               | 0.959                             | 0.988          | 0.996          | 0.967          | 0.983          |
| PH          | 0.860                           | 0.881                               | 0.870                             | 0.869          | 0.863          | 0.870          | 0.870          |
| SZ          | 0.818                           | 0.886                               | 1.000                             | 0.893          | 0.843          | 0.970          | 0.911          |
| SB          | 0.793                           | 0.851                               | 0.803                             | 0.813          | 0.800          | 0.807          | 0.814          |
| min.        | 0.793                           | 0.851                               | 0.744                             | 0.813          | 0.800          | 0.772          | 0.814          |

Based on the analysis of the results described in Table 8 it may be concluded that, out of the 20 variants, two architectural solutions, marked B2 and marked SB, respectively, are of importance. The former is optimal if the dominant criterion is project costs. On the other hand, the architectural solution marked SB is optimal when climate and energy-related criteria are the dominant criteria. This conclusion may be drawn from the analysis of both single-criteria and multi-criteria optimisation results, where the weights are set to prefer environmental criteria and their values are: 0.3–0.4. The sensitivity analysis of the weighted sum method clearly indicates that, if the building is designed (form, shape, and technical and material solutions) in accordance with the principles of sustainable development, such a design will dominate compared to other architectural solutions.

4. Discussion

In recent decades, scientists around the world have been looking for solutions that would significantly reduce the environmental impact of construction. There are many works devoted to this topic in the literature [29–34]. Despite a considerable presence in the literature, there are still many problems to be solved. This paper contributes to this trend and discusses the results of our research using LCA, which is the basis for the development of another tool to support architects in the early design phase. The purpose of using LCA in the early phase of architectural design is to find the shape of a building and its construction technology to minimise its building’s environmental impact.

In LCA analyses, the key is to choose stages of the building life cycle and impact categories. Often, the selection of indicators for assessing the environmental impact of buildings is determined by access to data, the importance of a given issue for the implementation of environmental policy and the labor-intensity of analysis. That was the case in this study. In Poland, energy sources based mainly on fossil fuels and unsustainable biomass cause high air pollution. Therefore, embodied energy and embodied carbon emissions have been chosen as the categories for a building’s environmental performance. Another problem is the selection of the values of the indicators of embodied energy and
embodied carbon emissions in building materials. In an era of globalization, Poles have access to materials from all over the world. Therefore, materials produced in countries where energy is mainly generated from renewable energy sources will have lower rates of embodied energy consumption and embodied carbon emissions. However, environmental impacts are still increasing due to transport. Obviously, the use of these products may change the results of the analysis. The adoption of the building energy standard is also of key importance. As shown in Figure 10, the higher the energy standard of a building, the greater the ratio of embodied energy is to operating energy. Therefore, the adoption of energy standards for buildings, other than those analysed in this paper, could affect the results of the analysis. This problem was partially presented by analyzing the building model designed in the passive house standard.

Figure 10. Dependencies between a building’s energy standard and embodied energy and energy consumed during operation. Source: Based on [8].

The use of multi-criteria optimization seems necessary when choosing the optimal shape and construction technology of a facility with the goal of minimal environmental impact. Of course, many optimization methods described in the literature can be used [28,29,35–40]. When choosing one of the simplest and most popular optimization methods, designers expect simple and easy-to-use tools to support the design process and the ability to perform a sensitivity analysis of the optimal solution.

5. Conclusions

The results of the research indicate the advisability of using the LCA method in the early phase of building design. LCA is particularly useful for determining the optimal shape, architectural form and positioning of transparent partitions, depending on the position of a given building’s environment.

The conducted analysis showed that, in the case of changing the shape of the building body in the F2 and A1/B1/C1 models, embodied carbon emissions are reduced by 12.55% while still maintaining the same technology and energy standard. Changing the energy standard in A2 and PH models while maintaining the same form of the building and similar technology reduces embodied carbon emissions by 5.36%. On the other hand, changing the technology itself while maintaining the same shape on the example of the A2 and SB models reduces embodied carbon emissions by 12.50%. The greatest effect was
achieved by changing the shape of the building as well as the technology, which can be seen most clearly in the examples of the F2 and SB models. In these cases, the reduction in embodied carbon emissions was 20.65%. This research shows that design decisions related to the shaping of a building’s body can influence changes in a building’s environmental performance throughout its life cycle. The best effect in the form of the lowest embodied carbon emission is achieved by optimizing the shape and technology of a building. When an architect chooses the shape and technology of a building, several criteria should be followed. It seems advisable to use multi-criteria optimization in this process. The method for selecting criteria and the weights assigned to them have a considerable impact on the optimization results. Therefore, it is always worth performing a sensitivity analysis of the optimal solution. Usually, with the same weights assigned to individual partial optimization criteria, an optimal solution that is insensitive to weight changes within 10% is found relatively quickly. The introduction of the dominant criterion (by giving it a weight above 0.5) very often changes the optimization result.

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