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Assessing the Sustainability of Alternative Structural Solutions of a Building: A Case Study

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Abstract: The implementation of sustainable solutions in the design of buildings is one of the main elements in achieving the transition to sustainability. The variety of structural elements and availability of sustainable materials, and the different preferences of clients, architects, and structural designers make the decision-making process difficult. This research aims to develop a decision model for applying to the early design stage. This work evaluates the sustainability of the load-bearing structures of a commercial building. Three types of load-bearing structures have been selected and compared concerning different physical parameters, cost of construction, cost of materials, technological dimensions (duration expressed in person-hours and machine-hours), and environmental impact. The methodology combines the building information modeling, sustainability criteria, and multi-criteria decision-aiding methods. The presented case study illustrates the proposed approach. The study revealed that multi-criteria decision aiding methods give the possibility to improve the selection process and to assess the sustainability of alternative structural solutions at an early stage of building design. The proposed decision model is versatile and therefore can be applied for different cases.

Keywords: sustainability; early design stage; structural solution; load-bearing structure; decision model; multi-criteria decision aiding; building information modelling

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1. Introduction

Resource depletion, degradation of ecosystems and climate change are challenges that have been emphasized recently in many research papers [1–4]. Moving towards sustainable processes in the whole life cycle of a building is seen as a solution to tackle those challenges and transform the cities into sustainable systems. One element in achieving this transition is the implementation of environmentally friendly solutions in the design of buildings and engineering structures.

The link between sustainable development and construction is clear. The construction industry is Europe's largest industrial employer accounting for about 10% of European GDP and has strong environmental and social impacts [5]. The building or structure designed using environmentally friendly materials is not necessarily sustainable. Successful sustainability cannot be realized considering only environmental issues. The latter have to be harmonized with the economic and social issues [6]. The adoption of sustainable practices involves the integration of all sustainable principles into the project life cycle and the inclusion of all responsible stakeholders [7]. Specifically, the design of sustainable buildings, which comply with the variety of sustainability categories, makes the role of the structural engineer very important. In the traditional approach of building design, structural engineers rarely assess the environmental dimension, which has been recognized in the modern integrated building design approach as one of the most important factors [8]. Structural engineering decisions have a major impact in the areas of waste generation, water consumption, energy use and environmental emissions [9]. The applications of sustainable construction principles into the design process can improve project sustainability [10]. However, additional cost, time and limited availability of green suppliers and information were reported as critical barriers [11]. Additionally, the variety of sustainable structural elements and availability of sustainable materials, the different preferences of clients, architects, and structural designers make the decision-making process difficult [4].

Sustainability is a multifaceted phenomenon that includes many competing goals. Sustainability by its broad extent carries categories for ensuring the needs and requirements of a project and building users and takes into account the environmental, economic and social aspects [12,13]. Sustainability of building solutions could be ensured by achieving the best quality of life in the spaces of a building by providing acoustical, visual and thermal comfort [14]. Constructability, selection of appropriate building systems, workability, durability and other design aspects mentioned by [15] as attributes of flexible design in terms of sustainability. For attaining a sustainable structural design, [16] assessed costs, CO_2 emissions, and service life. As stated by [17], the cost of energy consumption and carbon emissions must be calculated for every construction project, similar to material and labor costs. A sustainable design includes compliance with building standards, the production of repetitive elements and mass production that enables reduction in costs [5]. The complexity of commercial buildings and necessity to assess many sustainability categories requires that a robust optimization algorithm should be applied to select the optimum set of sustainable solutions [18].

The construction industry has been struggling for some time to improve its environmental performance. Comparisons of the eco-efficiency of construction materials used for load-bearing structures have been made [19,20]. Comparisons of slab construction techniques indicate overall embodied energy reductions up to 40% being achievable [21]. Diverse structural behavior, high structural quality, and performance in pursuing sustainability have been reported for scrap steel [10] and steel-making technologies for CO_2 capturing [22]. On the contrary, the production of cement and cement-based composites has been recognized as not being as eco-efficient as steel [23]. In the past decade, investigations have resulted in proposals on how to achieve better environmental and structural performance of concrete. In the last two decades, changing sustainability requirements resulted in a change in building design. It reflected in the models for shaping a sustainable building. For example, the steel construction expresses regular diagonals in the facade of the building, is easier and quicker to assemble and is highly compatible with the concept of a sustainable building [24].

The review of Liu et al. [25] revealed that the academic community recognized the potential of BIM in energy and environmental analysis and in sustainable design. The study of Olbina and Elliott [26] revealed that various stakeholder groups treat BIM as a universal Architecture, Engineering, and Construction (AEC) process that provides benefits on complex and simple projects. Recent research focuses on the integration of BIM and other related technologies, such as energy and carbon emission calculation, for speeding up the decision processes and to enable structural designers and other professionals to deliver their building in a more efficient manner [27]. A review of Olawumi and Chan [28] revealed the significant impacts of BIM in several areas of the AEC industry such as design, construction, facility management, safety, and sustainability. BIM can improve the processes of prefabrication, which is considered to be an efficient method to reduce building waste, energy consumption, and CO_2 emissions [29].

Due to increasing levels of competition, construction companies are considering corporate social responsibility with regard to the social and environmental factors, which define this concept and are included in corporate commitments to the contribution to sustainable economic development [30]. However, the importance of incorporating sustainable development principles in early project stages is not enough understood by project stakeholders. Designers and structural engineers should be consulted even in the feasibility stage for professional advice on various alternatives and their influences on the project sustainability [31]. Moreover, various stakeholders' categories have to be considered to ensure the comprehensive assessment of all sustainability aspects, especially building-specific social impacts [32].

There are many comprehensive sustainability assessment techniques, such as the well-known examples of The Leadership in Energy and Environment Design (LEED) and Green Globes in the USA, the Building Research Establishment Environmental Assessment Method (BREEAM) in the UK, the Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB) in Germany, the Building Environmental Assessment Method (BEAM Plus) in Hong Kong, the Comprehensive Assessment System for Built Environment Efficiency (CASBEE) in Japan, Green Star in Australia, etc. However, those are time-consuming in their application and do not consider the economic aspect, which is contrary to the ultimate principle of sustainable development. On the one hand, there is a need for environmentally friendly solutions with minimum energy consumption and waste generation; on the other hand, the investor intends to pursue cost-effective projects [33]. In this regard, the lack of cost analysis is the main weakness of the mentioned sustainability assessment tools [34]. Additionally, the mentioned Sustainability Assessment and Certification Systems, although adequate to evaluate the sustainability of a building component, is not an appropriate tool in support of architects during the design process [35]. Moreover, most authors who have analyzed sustainable design methodology note that the cost of eco-efficient products is high [36–39]. The weaknesses of sustainability assessment tools have been reported, thus stating the immaturity of sustainable product design tools [40]. Samani et al. [41] concluded that one of the major drawbacks of studies on sustainable buildings is that technologically oriented studies are normally lacking in the social dimension of sustainability, while more technical aspects need to be integrated into the socially oriented studies.

More research, including experiments, are needed to test the theoretical innovations in sustainable design and construction proposed by various scientists. A lot of work remains to be done in this area to make the green project financially attractive to the investor. The reported weaknesses of design and sustainability assessments led to the conclusion of a need for fast in application, simple and reliable methods to assess the sustainability of structural solution at the early design stages.

In this study, we propose the approach for sustainability assessment in the early design stage. The aim of this research is to develop a criteria system and decision model for assessing the sustainability of alternative structural solutions in the early design stage. The methodology combines building information modeling (BIM), sustainability criteria and multi-criteria decision aiding methods. The sustainability criteria include physical, economic, technological and environmental aspects. The multi-criteria decision aiding methods included in the approach in order to improve the selection process and to assess the sustainability of alternative structural solutions at an early stage of building design. BIM tools were applied for gathering building data necessary for multi-criteria analysis.

2. Research Methodology

The present study adopts a methodology consisting of an analysis of literature, an expert assessment, and a case study analysis. The sustainability categories selected based on the analysis of the existing studies in the field of sustainable structural design. By using a 3-step Delphi study approach, experts set up the feasible alternatives, selected the criteria system, and determined the weights of criteria. Furthermore, in the case study, the criteria values were calculated and a multi-criteria assessment of the alternatives was performed. The next sections describe in detail the steps followed in the work methodology.

2.1. Sustainability Categories

As it was mentioned above, sustainability by its broad umbrella carries environmental, economic and social categories for ensuring the needs and requirements of a project and users. Variety of technologies distinguish construction processes and requires analyzing the technological aspects as separate and important sustainability category. The sustainability categories used in this research were selected based on the traditional approach and alternative insights, and include environmental, economic, technological and social categories (Figure 1). A sustainability assessment of alternative solutions implies the use of many criteria; therefore, the model proposes the application of multi-criteria decision adding (MCDA) methods as reliable and versatile tools for decision-making [42]. Additionally, dealing with many alternatives the decision-maker gathers a big amount of data. The existence of human factors leads to distorted incomplete data and finally to the question of the reliability of gathered data sets. The risk of unreliable data and information could be reduced if automated data gathering and processing are used. The application of Building Information Modeling (BIM) tools provide the solutions, thereat, the model proposes the inclusion of BIM tools for gathering reliable data (e.g., quantities) necessary for sustainability assessment (Figure 1).

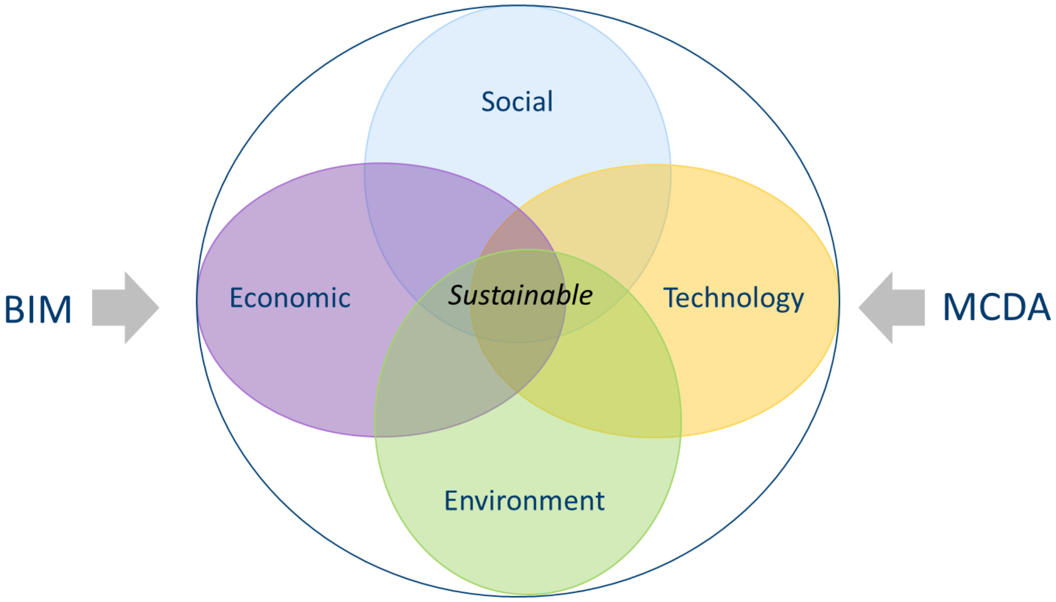


Figure 1. Sustainability categories used in research.

The sustainability of building solutions could be ensured by achieving the best life quality in the spaces of a building by accomplishing acoustical, visual and thermal comfort. Paying attention to the possibility of realizing functions and users' comfort and satisfaction, the criteria for the sustainability assessment of alternative structural solutions were set (Table 1). The initial set of sustainability criteria chosen based on the literature analysis and expert assessment through the iterations of the Delphi technique. Users' comfort and satisfaction were reflected by including, in a proposed set of criteria, the relevant categories expressed by physical criteria—such as the "total area of indoor spaces", that are important for end-users of building.

Table 1. Proposed set of criteria for the sustainability assessment of alternative structural solutions.

Criteria
Social (e.g., different physical parameters like total area of indoor spaces, m^2; etc.)
Economic (e.g., cost of construction works, Euros; cost of materials, Euros; etc.)
Technological (e.g., person hours; machine hours; etc.)
Environmental (e.g., energy consumption, MJ; greenhouse gas emissions, kg CFC-11 eq; etc.)

2.2. *A hybrid MCDA Model for Decision-Making*

The present study adopts a triangular approach, consisting of an analysis of literature, expert interviews, and a follow-up case study analysis. The methodology applied includes following steps:

Step 1. A parametric model of building was created, and feasible alternatives formed.

Step 2. Based on the literature analysis, the criteria system for the selection of sustainable structural solutions for buildings was created.

Step 3. The weights of the criteria were determined by experts through a 3-step Delphi study approach.

Step 4. This step includes calculation of values of physical criteria of alternative structural solutions, analysis of alternative construction technologies, determining economic criteria (costs) of implementing alternative structural solutions, and assessing the environmental performance of alternative structural solutions.

Step 5. Application of the multi-criteria aiding methods SAW, ARAS and COPRAS and assessment of alternative structural solutions in terms of sustainability. This step also includes the analysis of results.

Figure 2 depicts the main steps of the methodology followed in this research.

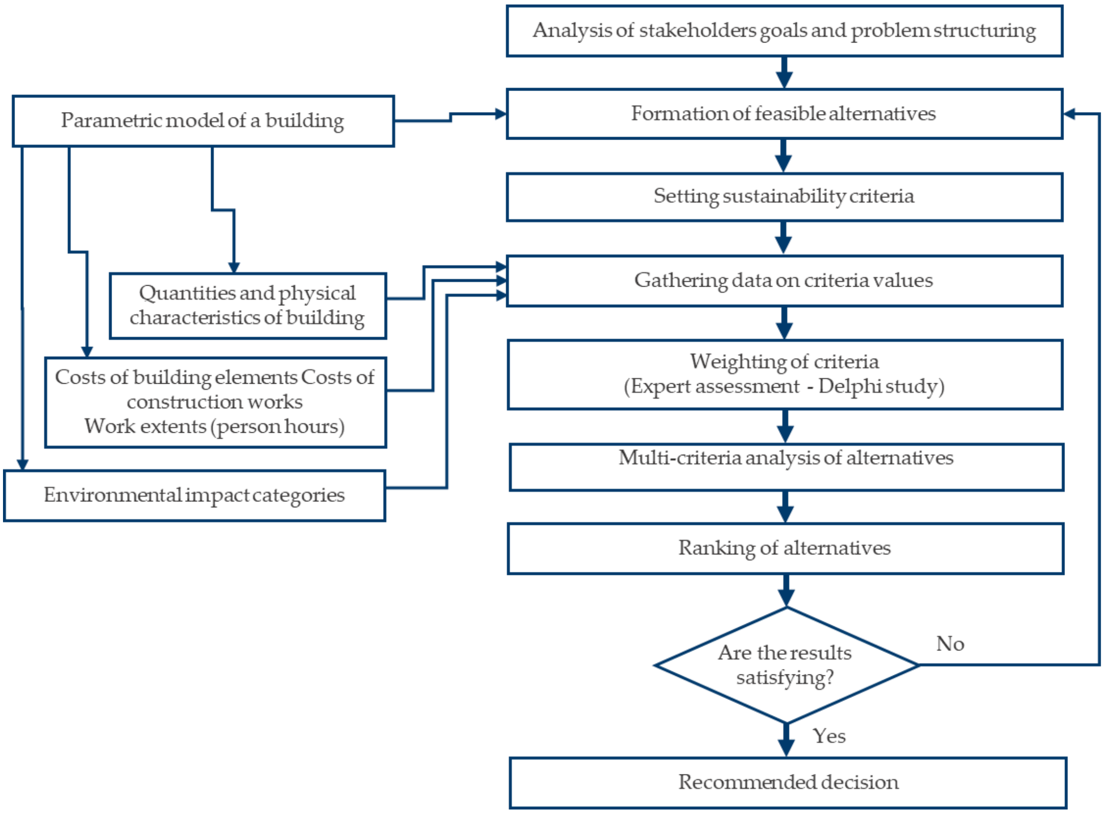


Figure 2. The structure of the hybrid decision model, based on the multi-criteria aiding methods and Delphi technique.

Though a structure of a building consists of many components, this study focused on the load-bearing structures of commercial buildings. In the case study, we considered only three types of load-bearing structures—building bearing structure made from reinforced concrete prefabricated elements and structural steel, bearing elements made of prefabricated reinforced concrete, building frame made from monolithic reinforced concrete.

3-step Delphi study approach applied for expert assessment of criteria weights presented in Section 2.3. Multi-criteria aiding methods SAW, ARAS and COPRAS applied for the assessment of alternative structural solutions presented in Sections 2.4–2.6.

Dozens of multi-criteria decision aiding methods have been developed recently to address a large variety of problems emerging in civil engineering [8,43–46]. They classified into two classes depending on how they combine the data: discrete MCDM or MADM and continuous MODM (Multi-Objective Decision Making) optimization methods [44]. They all require the definition of options and criteria, and most of them demand a measure (e.g., weights) for assessing the relative significance of the criteria.

However, the application of a single function in the decision-making process is not a sufficient condition. There is no single method that could be suitable for solution of all problems. Different MCDM methods sometimes yield different results [42]. Researchers and practitioners have recently increasingly supported the use of hybrid methods, because integrating different utility functions in one decision-making model can increase the reliability and transparency of the decision-making process in real-life situations [47]. Integrated approaches most frequently use two or more MCDM methods or a combination of the MCDM methods and other decision support approaches [43–51].

The typical MCDM problem has the task of ranking a finite number of decision alternatives explicitly described in terms of different decision criteria, which have to be taken into account simultaneously. This work uses a hybrid method, i.e., a combination of Delphi technique, SAW, ARAS and COPRAS methods. The method SAW (Simple Additive Weighting) is one of the simplest and most widely used multiple criteria assessment methods [52]. However, SAW uses only criteria of maximizing optimality function, while criteria with minimizing optimality direction should be converted into the maximizing ones prior to their application. This limitation is eliminated in the method COPRAS (Complex Proportional Assessment). In COPRAS method, the influence of maximizing and minimizing criteria assessed separately. The calculation results obtained by COPRAS method depend on the number of minimizing criteria and their values. The comparative analysis [52] of SAW and COPRAS methods revealed that the calculation results obtained by these two methods might differ. Therefore, the third method needed to more accurately evaluate and validate the calculation results. For this purpose, the ARAS (Additive Ratio Assessment) method [53] was applied. According to the ARAS method, the utility function value determining the complex efficiency of a feasible alternative is directly proportional to the relative effect of values and weights of the main criteria [53].

2.3. Delphi Technique

The Delphi study is an iterative process, based on the principle that decisions from a structured group of experts are more accurate than from individual or unstructured assessment. The Delphi technique has been used in many professional fields, such as facilities management [42], road engineering [54], healthcare [55], energy [56], manufacturing [57] and education [58].

The key methodological features of the Delphi study include a multi-stage procedure, ensured anonymity, feedback and experts' independent views. The Delphi technique was applied in this study to select the main criteria, reject the less important, and to assess the weights of criteria.

This Delphi study was conducted in three rounds (Figure 3). First, the group of experts chose the facilitator—a neutral university expert who had experience in Delphi technique applications. During the Delphi study, experts exchanged viewpoints and each independently gave estimates to the facilitator. The experts had a task to decide on a set of criteria that should be relevant and universal for application in other cases. Ten experts of experienced and knowledgeable people from construction companies and academic institutions were selected for the panel (Table 2). Experts were required to have knowledge and experience in the field of civil engineering, participated in international projects, and performed consultancies in the construction sector. During the evaluation process, the main criteria for selection were that candidates had to have a masters' degree or higher and five or more years of experience in the field of civil engineering.

In the first round, experts were asked to review the object-related sustainability criteria, to reject the less relevant, and then to decide on the initial set of sustainability criteria. In the second round, experts were asked to set up the final list of sustainability criteria and to provide insights on comparative analysis of criteria. In the third round, experts were asked to decide on the weights of criteria necessary for the multi-criteria assessment of alternatives. When experts assigned the weights for the criteria, the compatibility of expert opinions was checked. The results of the expert assessment were summarized by the mean calculation.

After the experts identified the weights of criteria, the multi-criteria decision aiding methods were applied to rank the alternatives.

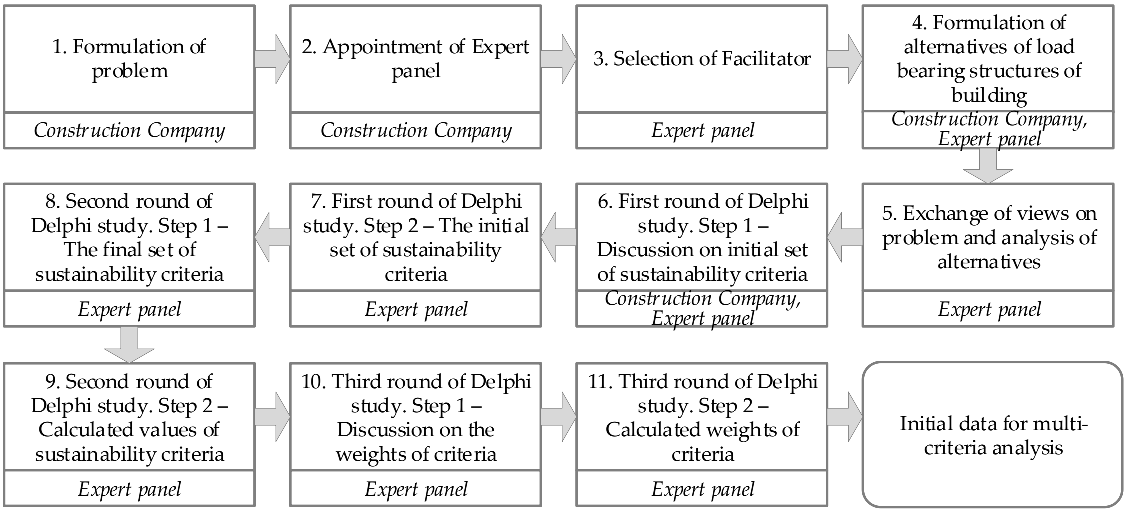


Figure 3. The iterations of Delphi technique adapted for the study.

Table 2. Characteristics of experts.

Experts *	Education	Employment Place and Position	Experience (years)
Expert 1	Higher, MSc	Construction Company, structural engineer	6
Expert 2	Higher, MSc	Construction Company, project manager	10
Expert 3	Higher, MSc	Construction Company, head of the department	9
Expert 4	Higher, MSc	Construction Company, structural engineer	5
Expert 5	Higher, MSc	Construction Company, project manager	33
Expert 6	Higher, MSc	Construction Company, structural engineer	5
Expert 7	Higher, MSc	Construction Company, structural engineer	5
Expert 8	Higher, PhD	University, Assoc. Prof. Dr.	15
Expert 9	Higher, PhD	University, Assoc. Prof. Dr.	10
Expert 10	Higher, PhD	University, Assoc. Prof. Dr.	10

* The names of the experts and the company's name are not specified for confidentiality reasons.

2.4. Simple Additive Weighting Method

Simple Additive Weighting (SAW) method is a widely known and practically used method [52,59]. The sum of the weights of all criteria must be equal to one ($\sum_{i=1}^{n} q_i = 1$). The problem is solved by the method in the following order:

Step 1. An initial decision matrix D is formed:

$$D = \begin{bmatrix} x_{11} & x_{12} & x_{13} & \dots & x_{1m} \\ x_{21} & x_{22} & x_{23} & \dots & x_{2m} \\ \dots & \dots & \dots & \dots & \dots \\ x_{n1} & x_{n2} & x_{n3} & \dots & x_{nm} \end{bmatrix}. \tag{1}$$

Step 2. Normalization (or transformation) of decision matrix to obtain dimensionless values:

$$r_{ij} = \frac{x_{ij}}{x_i^{\max}}; \tag{2}$$

$$r_{ij} = \frac{x_i^{\min}}{x_{ij}}. \tag{3}$$

where r_{ij} is converted i-th criterion's value for j-th alternative, $x^{\min}$ is the smallest i-th criterion's value and the $x^{\max}$ is the largest criterion's value for all compared alternatives.

Formula (2) is used for the transformation of criteria if maximum values are preferable. Formula (3) is used for the transformation of criteria if minimum values are preferable.

Step 3. The sum S_j of the weighted normalized values of all the criteria is calculated for the *j*-th object:

$$S_j = \max_j \sum_{i=1}^{n} r_{ij} \times q_i, \quad j = 1, \ 2, \ 3, \ldots, \ m. \tag{4}$$

Step 4. Ranking of alternatives and selection of rationale. The largest value of the criterion S_j corresponds to the rational alternative. The alternatives compared should be ranked in the decreasing order of the calculated values of the criterion S_j.

2.5. ARAS Method

The Additive Ratio Assessment (ARAS) method [53] was applied in following steps:

Step 1. The decision-making matrix is composed.

$$X = \begin{bmatrix} x_{01} & \cdots & x_{0j} & \cdots & x_{0n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{i1} & \cdots & x_{ij} & \cdots & x_{in} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mj} & \cdots & x_{mn} \end{bmatrix}; \qquad i = \overline{0, \ m}; \ j = \overline{1, \ n}\,, \tag{5}$$

If optimal value of j criterion is unknown, then:

$$\begin{aligned} x_{0j} &= \max_i x_{ij}, && if \max_i x_{ij} \ is \ preferable, \ and \\ x_{0j} &= \min_i x^*_{ij}, && if \min_i x^*_{ij} \ is \ preferable. \end{aligned} \tag{6}$$

Step 2. The purpose of this step is to receive dimensionless weighted values of the criteria. The initial values of all the criteria are normalized defining values $\overline{x}_{ij}$ of normalized decision-making matrix $\overline{\mathrm{X}}$:

$$\overline{\mathrm{X}} = \begin{bmatrix} \overline{x}_{01} & \cdots & \overline{x}_{0j} & \cdots & \overline{x}_{0n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \overline{x}_{i1} & \cdots & \overline{x}_{ij} & \cdots & \overline{x}_{in} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \overline{x}_{m1} & \cdots & \overline{x}_{mj} & \cdots & \overline{x}_{mn} \end{bmatrix}; \qquad i = \overline{0, \ m}; \ j = \overline{1, \ n}\,. \tag{7}$$

The criteria, whose preferable values are high, are normalized as follows:

$$\overline{x}_{ij} = \frac{x_{ij}}{\sum\limits_{i=0}^{m} x_{ij}}\,. \tag{8}$$

The criteria, whose preferable values are low, are normalized by applying two-stage procedure:

$$\begin{aligned} x_{ij} &= \tfrac{1}{x^*_{ij}}; \\ \overline{x}_{ij} &= \tfrac{x_{ij}}{\sum\limits_{i=0}^{m} x_{ij}}. \end{aligned} \tag{9}$$

Step 3. The next step is defining the normalized-weighted matrix $\hat{\mathrm{X}}$. It is possible to evaluate the criteria with weights $0 < w_j < 1$. The values of weight w_j are usually determined by the expert assessment method. The sum of weights w_j would be limited as follows:

$$\sum_{j=1}^{n} w_j = 1. \tag{10}$$

$$\hat{X} = \begin{bmatrix} \hat{x}_{01} & \cdots & \hat{x}_{0j} & \cdots & \hat{x}_{0n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \hat{x}_{i1} & \cdots & \hat{x}_{ij} & \cdots & \hat{x}_{in} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \hat{x}_{m1} & \cdots & \hat{x}_{mj} & \cdots & \hat{x}_{mn} \end{bmatrix}; \qquad i = \overline{0,\ m};\ j = \overline{1,\ n}\,. \tag{11}$$

Normalized-weighted values of all the criteria are calculated as follows:

$$\hat{x}_{ij} = \overline{x}_{ij} w_j\,; \qquad i = \overline{0,\ m}, \tag{12}$$

where w_j is the weight of the j criterion and $\overline{x}_{ij}$ is the normalized value of the j criterion.

Step 4. The values of optimality function are determined as follows:

$$S_i = \sum_{j=1}^{n} \hat{x}_{ij}\,; \qquad i = \overline{0,\ m}, \tag{13}$$

here S_i is the value of optimality function of i alternative.

The greater the value of the optimality function S_i, the more effective the alternative. The priorities of alternatives can be determined according to the value S_i.

Step 5. The degree of the utility is determined by a comparison of the alternative, which is analyzed, with the ideally best one S_0. The equation used for the calculation of the utility degree K_i of an alternative a_i is given below:

$$K_i = \frac{S_i}{S_0}; \qquad i = \overline{0,\ m}, \tag{14}$$

where S_i and S_0 are the optimality criterion values, obtained from Equation (10).

The calculated values K_i are in the interval [0; 1] and ordered in an increasing sequence, which is the wanted order of preference.

2.6. COPRAS Method

The preference ranking method of complex proportional assessment (COPRAS) [60] was applied in the following steps:

Step 1. The initial decision-making matrix is normalizing with the goal is to get the dimensionless values. The authors use normalization with the weights:

$$\overline{x}_{ij} = \frac{x_{ij}}{\sum\limits_{j=1}^{n} x_{ij}};\ j = \overline{1, n};\ i = \overline{1, m}, \tag{15}$$

Here x_{ij}—value j of i criterion; m—the number of criteria; n—the number of compared evaluations; q_i—the weight of i criteria.

Step 2. Normalized-weighted values of all the criteria are calculated as follows:

$$\hat{x}_{ij} = \overline{x}_{ij} \cdot q_j \tag{16}$$

Here j—the criterion, q_i—the weight of j criterion.

Step 3. The sums of minimizing S_{-j} and maximizing S_{+j} normalized indicators calculated:

$$S_j^+ = \sum_{i=1}^{m} \hat{x}_{ij}^+, \; S_j^- = \sum_{i=1}^{m} \hat{x}_{ij}^-. \tag{17}$$

Step 4. The relative importance of the alternatives according to the characterizing positive S_{+j} and negative S_{-j} qualities is determined. The relative importance Q_j of each alternative a_j is determined by the following formula:

$$Q_j = S_j^+ + \frac{S_{\min} \cdot \sum_{j=1}^{n} S_j^-}{S_j^- \cdot \sum_{j=1}^{n} \frac{S_{\min}}{S_j^-}}, \tag{18}$$

where $S_{\min} = \min_j S_j^-, \; j = 1, \ldots, n.$

Step 5. The utility degree of each alternative is determined:

$$N_j = \frac{Q_j}{Q_{\max}} 100\%, \tag{19}$$

where $Q_{\min} = \max_j Q_j, \; j = 1, \ldots, n.$

Step 6. Ranking of the alternatives. The priority order of compared alternatives is determined based on their relative importance Q_j. The alternative with higher relative importance has higher priority (or rank), and the alternative with the highest relative importance is the most acceptable:

$$A^* = \left\{ A_i \middle| \max_i Q_i \right\} \tag{20}$$

3. Case study

3.1. Description of Case Study Building

The object of this study is the commercial building adapted to the cultural purpose (cinema). The designed building has eight cinema halls. The building structures will be mounted on the existing multistorey parking garage (Figure 4). The distances between the axles of the new building are 16.28 m. The height of the existing building is 9.5 m and the height of the new building is 15.5 m. The total height of the building is 25 m.

The layout of the load-bearing structures of the new building is limited by the layout of the load-bearing structures of the existing building. New load-bearing structures may only be installed at the intersection of the existing car parking building axles. In other words, the newly installed columns must be above the columns of the car parking building. Otherwise, the structures of an existing building may not withstand the bending moment that may result from the action of concentrated forces. Besides, the mass of the constructions of the building being designed is limited. If the weight of the structures is too large, the foundation of the car parking building may not withstand, and dangerous seating or deformation of the existing foundation will occur. In this case, the building may even collapse. The large spans expected in the new building. Therefore, it greatly influences the choice of structures. An apartment building is planned to be built next to the existing car park. However, it has not been considered, as the object of study will not be affected by the construction of the apartment building.

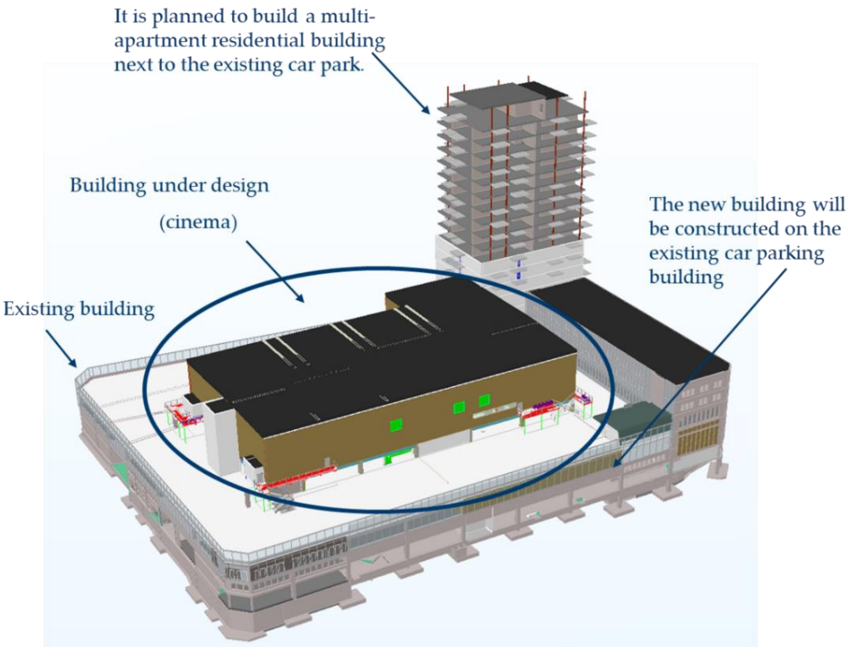


Figure 4. Structural model of the building under investigation.

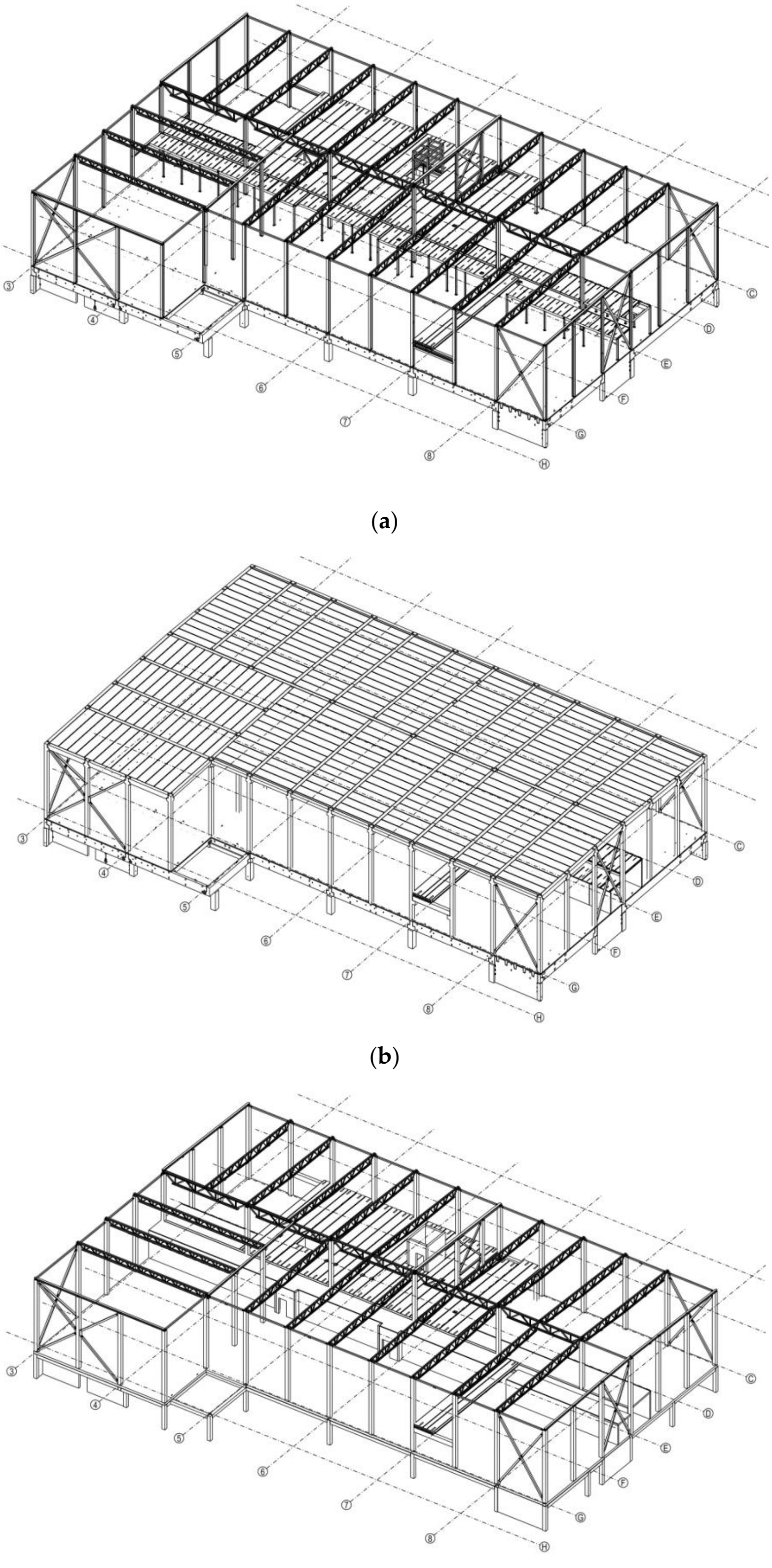
Alternative structural solutions:

1. Alternative A1. Building frame made of reinforced concrete prefabricated elements with metal bearing elements (Figure 5a).
2. Alternative A2. Prefabricated reinforced concrete bearing elements (Figure 5b).
3. Alternative A3. Building frame made of monolithic reinforced concrete (Figure 5c).

The load-bearing structure of the first alternative of the case building is the frame made of reinforced concrete prefabricated elements with metal bearing elements (Figure 5a). Reinforced concrete and metal elements pre-fabricated in factories and transported to the construction site. The elements are transported in the sequence according to the installation process. This solution solves the problem of storage at the construction site. As the object under consideration is a newly built cinema mounted on an existing parking lot, there will be no possibility of temporary storage of structural elements. Therefore, it is best to install the structures directly from the vehicle. To speed up the assembly of the building frame, the structures are bolted instead of welding. The roof covering is mounted on trusses to create large spaces in the building. In this way, a span of more than sixteen meters is covered.

The second alternative of the load-bearing structure is the frame of reinforced concrete prefabricated elements (Figure 5b). As in the first case, pre-fabricated reinforced concrete elements transported from the factory directly to the construction site. The elements are transported according to the installation process, thus solving the problem of element storage. The structures also mounted using bolts. The roof structure is installed using pre-stressed reinforced concrete products. Precast concrete hollow core roof slabs of six meters length are rested on inverted T-beams. In this way, a span of more than sixteen meters is covered.

The third alternative of the load-bearing structure is the monolithic reinforced concrete frame (Figure 5c). The struts, turrets, wooden beams, plywood and other elements needed for concreting the slabs are brought to the construction site by crane. The workers install the slab formwork by hand. The workers at the construction site also bind the reinforcement frames. Concrete from the concrete mixer is pumped to the formwork. The formwork used to form walls and columns is mounted using the crane. To create large spaces in the building, the roofing is mounted on trusses. In this way, a span of more than sixteen meters is covered.



(**a**)

(**b**)

(**c**)

Figure 5. Alternative structural solutions of the building under investigation: (**a**)—alternative A1; (**b**)—alternative A2; (**c**)—alternative A3.

3.2. Assumptions

The following assumptions are made in this study:

- The total weight of the building under construction must not exceed the calculated allowable as it will be built on an existing car park.
- The building must meet the architectural requirements set for cultural buildings. The purpose of the building is a cinema theatre, so it is important not to reduce the space of the premises when creating alternatives. To ensure this condition, the list of criteria must include the area and volume of the premises. This indicator was not used in the final assessment, because designers of the case study building ensured almost the same values for all alternatives.
- Environmental impact assessment is only carried out for the production stage. Small details and elements (nails, electrodes, etc.) have not been evaluated in material quantity analysis.

3.3. Simulation Tools

Structures of real case-building were analyzed and calculated with the help of the software "Autodesk Robot Structural Analysis". Using this software load and element calculations were obtained. A parametric building model was composed using structural BIM software Tekla Structures. This software can make lists of all quantities of elements. Using this feature, quantities (units), volumes (m^3), areas (m^2) and weights (t) were accurately calculated. Economic calculations were made using the cost estimating software "ProSama 5G". Using this program, a new complex was created (K001) with three new objects (reinforced concrete prefabricated elements with metal bearing elements, prefabricated reinforced concrete bearing elements, and monolithic reinforced concrete) and three estimates ("GB-Metal", "GB Prefabricated", "Monolith"). The prices of prefabricated structural elements used were from the price list of (UAB "Sistela"). Energy consumption and environmental impact parameters were determined by applying the life cycle assessment (LCA) software package "SimaPro".

The panel of experts was composed of qualified construction professionals and determined the weights of the criteria. Multi-criteria aiding methods SAW, ARAS and COPRAS used for the assessment of alternatives and the selection of the rational. Intermediate and final results were analyzed by systematizing and graphically displaying calculated data. Tools, methods and information flows for the analysis of real case building depicted in Figure 6.

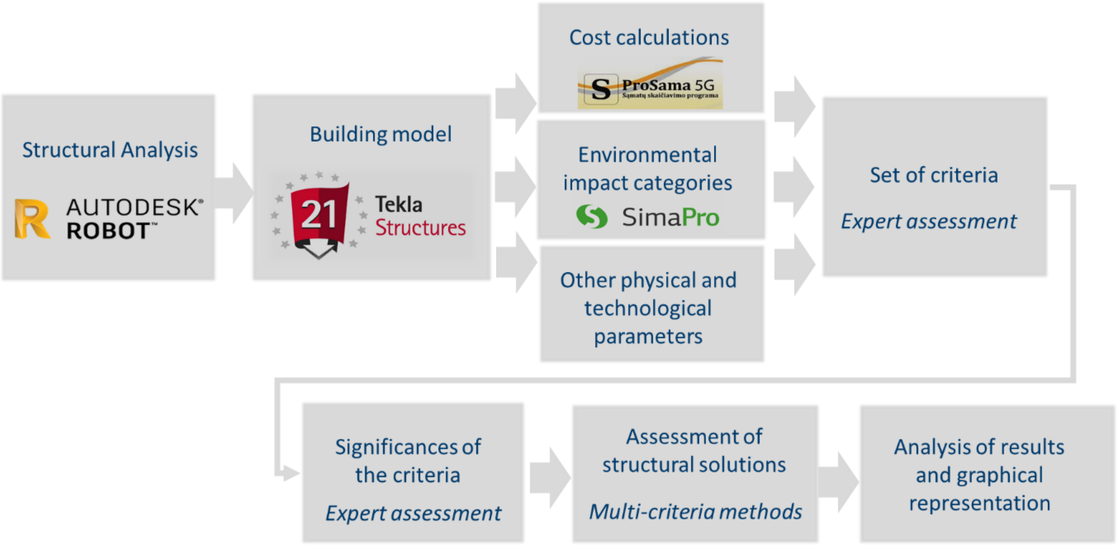


Figure 6. Information flow for the analysis of real case building.

3.4. Set of Criteria for the Sustainability Assessment

As it was mentioned in Section 3.1, the sustainability categories used in this research include environmental, economic, technological and social categories. Initial set of criteria for the sustainability assessment of alternative structural solutions of case building presented in Table 3.

Table 3. Initial set of criteria for the sustainability assessment of alternative structural solutions of case building.

Criteria	**Measuring Units**	
Physical criteria		
R1	Total area of indoor spaces	m^2
R2	Weight of structures	t
R3	Maximum load on columns in the peak load area	kN
Economic criteria		
R4	Costs of works	Euro
R5	Costs of materials	Euro
Technological criteria		
R6	The amount of work performed by the average worker in one hour	Person-hours
R7	The amount of work performed by the machines and equipment	Machine-hours
Environmental criteria		
R8	Energy consumption for production of materials	MJ
R9	Global warming potential (GPW)	kg CO_2 eq/unit
R10	Greenhouse gas emissions (CFC-11) *	kg CFC-11 eq

The following sections provide a detailed description of how the criteria values are defined, as well as an analysis and comparison of the parameters of the structural alternatives.

3.5. Analysis of Parameters of Structural Solutions

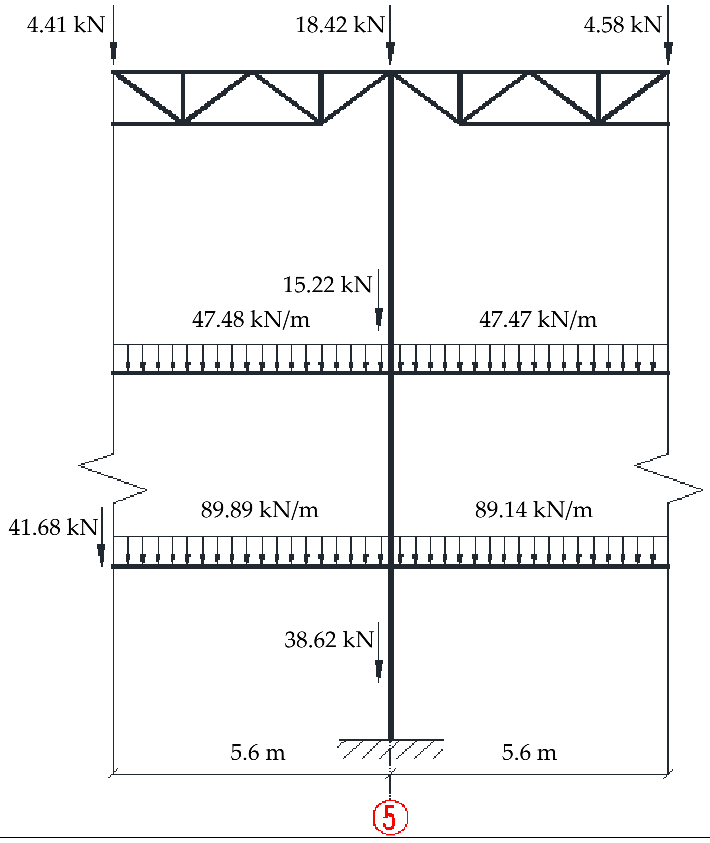
3.5.1. Calculation of Physical Parameters

Using Tekla Structures software, the alternatives of load-bearing structures of case building simulated (Figure 5). With the help of the Tekla Structures, the bills of quantities of all elements were generated. Using this feature, the quantities, volumes and masses of the elements were accurately estimated. The quantities are summarized in Table 4.

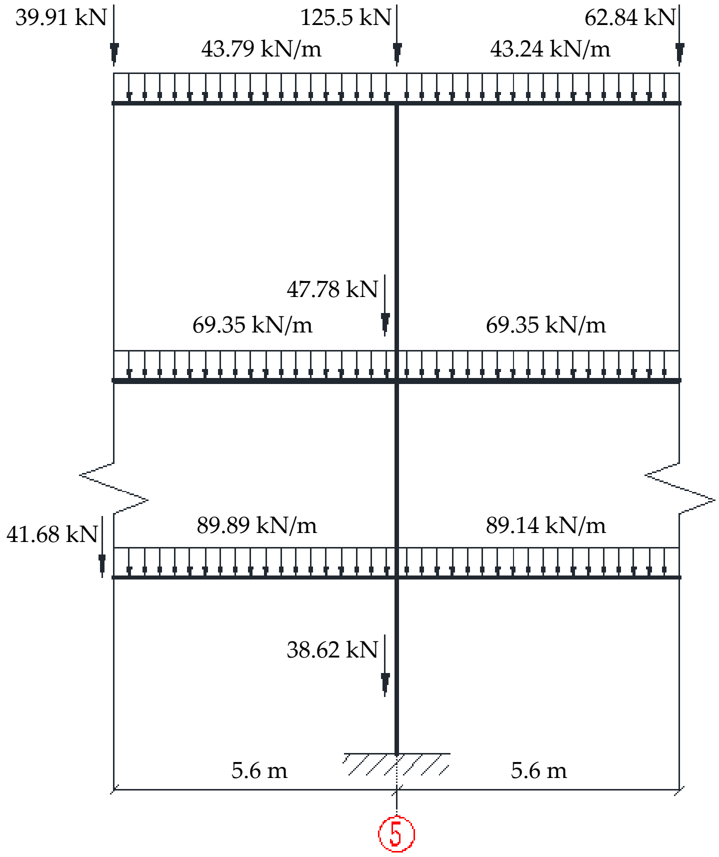
Table 4. Physical parameters of alternative structural solutions.

Type of Material	**Number of Elements**			**Volume of Elements, m^3**			**Weight of Elements, t**		
	A1	**A2**	**A3**	**A1**	**A2**	**A3**	**A1**	**A2**	**A3**
Reinforced concrete	262	777	237	730	1336	1143	1825	3341	2859
Structural steel	902	519	181	16	1	5	126	7	37

Using the mass of frame elements, the load on the columns in the area of the maximum load was calculated. The maximum load is on the columns at the intersection of the 5-E axes. The load diagrams and calculated loads depicted in Figure 7.

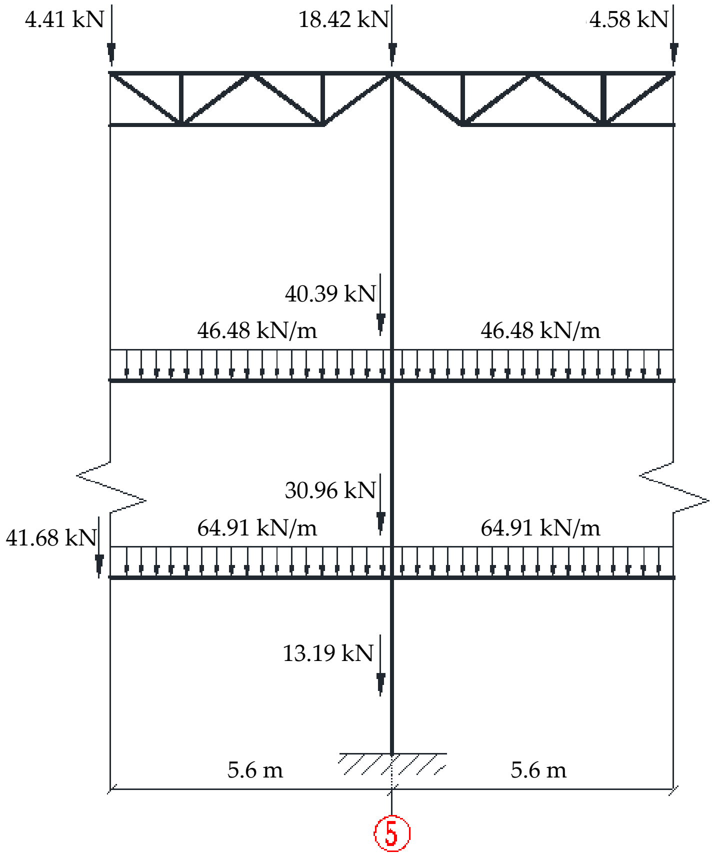


(**a**) Calculated load: 1657 kN



(**b**) Calculated load: 2623 kN

Figure 7. *Cont.*



(**c**) Calculated load:
1360 kN

Figure 7. Calculated loads on one column in the maximum load area: (**a**) alternative 1—building frame made of reinforced concrete prefabricated elements with metal bearing elements); (**b**) alternative 2—prefabricated reinforced concrete frame); (**c**) alternative 3—building frame made of monolithic reinforced concrete).

When assessing the entire weight of the structures, the mass of the building is the first alternative is 42% lower compared to the second and 33% lower compared to the third alternative (Figure 8).

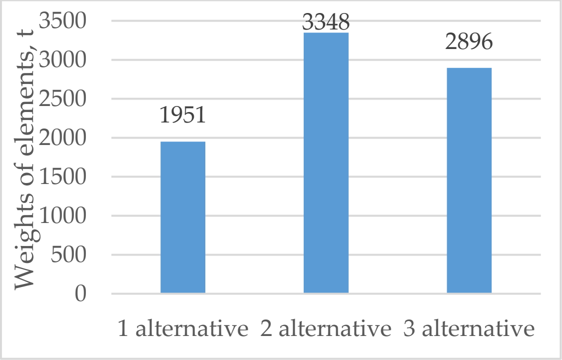


Figure 8. Comparison of weights of alternative load bearing structures (t).

The load on the column in the maximum load area in the third alternative is 18% lower compared to the first and 48% lower compared to the second one (Figure 9).

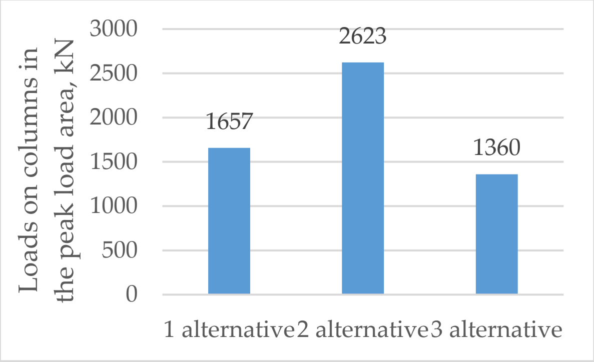
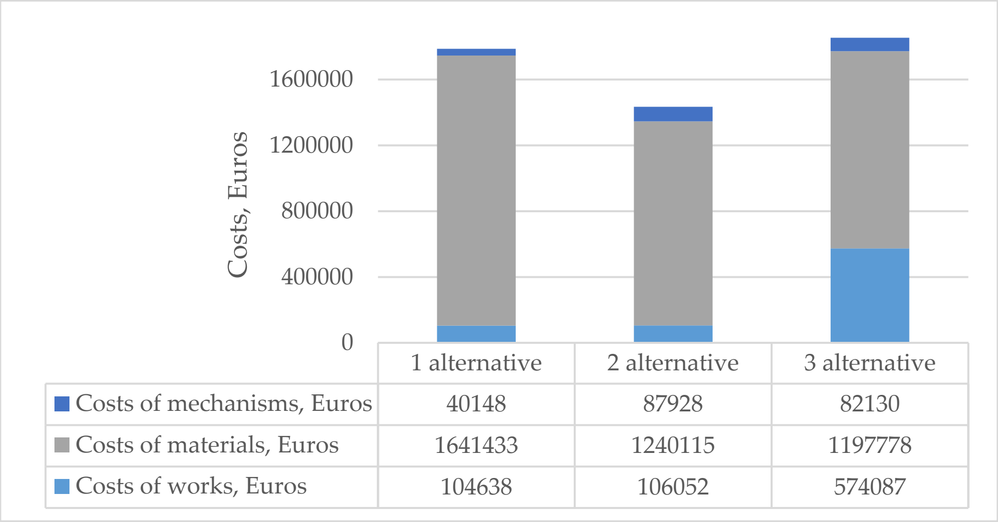


Figure 9. Comparison of maximum loads on columns in the peak load area (kN).

3.5.2. Calculation of Economic Criteria

This section provides the cost estimates for alternative structural solutions. The necessary initial data—quantities of structural elements (units), volumes (m^3), areas (m^2) and weights (t)—are calculated using the "Tekla Structures" software. Economic calculations were made using the cost estimating software "ProSama 5G". Costs were divided into three categories: costs of works, costs of materials, and costs of mechanisms.

The comparison depicted in Figure 10 shows that the cost of the work is lowest in the first alternative, i.e., 1.3% lower compared to the second and 82% lower compared to the third alternative. Building materials are cheapest in the third alternative, i.e., 27% cheaper compared to the first and about 3% cheaper compared to the second. The cost of the mechanisms is the lowest in the first alternative, i.e., about 54% lower compared to the second and 51% lower compared to the third. The total cost of installing a building frame is the lowest for the second alternative. It is cheaper by 20% compared to the first alternative and 23% compared to the third alternative.



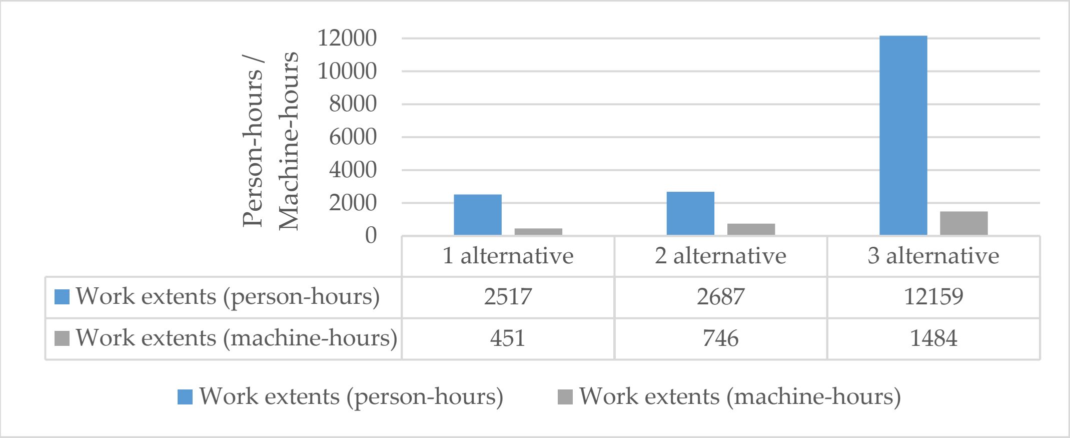
	1 alternative	2 alternative	3 alternative
■ Costs of mechanisms, Euros	40148	87928	82130
■ Costs of materials, Euros	1641433	1240115	1197778
■ Costs of works, Euros	104638	106052	574087

Figure 10. Comparison of costs of installing the building frame.

3.5.3. Calculation of Technological Criteria

The technological criteria in this study expressed by the work amount made by humans and machines to perform the specific unit of work. In this study, we used national normative person-hour and machine-hour rates for construction works. Total work amounts in person-hours and machine-hours for all alternatives calculated by multiplying normative values by total work volume.

The comparison of work amounts depicted in Figure 11 shows that the third alternative requires the highest work amounts, whereas the first requires the least. Required human work amounts (person-hours) for the first alternative are 6% lower compared to the second and about 80% lower compared to the third. Required machine work amounts (machine-hours) are also lowest in the first alternative, i.e., about 40% lower compared to the second and about 70% lower compared to the third alternative. Work amounts are used to estimate the duration of construction processes. Therefore, when evaluating the results obtained, it is concluded that the construction time of the third alternative would be the highest.



	1 alternative	2 alternative	3 alternative
■ Work extents (person-hours)	2517	2687	12159
■ Work extents (machine-hours)	451	746	1484

Figure 11. Comparison of technological parameters.

3.5.4. Calculation of Environmental Criteria

The environmental impact assessment was carried out at the material production stage. Three impact categories—primary energy demand (PE), global warming (GW) potential, and ozone layer depletion (OLD) are set for each alternative. The study analyzes the primary energy used for the production of building materials, the emissions of CO_2 that contributes to global warming, and the emissions of ozone depleting gases. The data needed to perform these calculations are obtained from the SimaPro LCA software database.

The comparison of energy required to produce building materials depicted in Figure 12 shows that the least amount of reinforcing steel needed for the first alternative, so the energy required to produce this material is the lowest, i.e., 47% lower compared to the second and 10% lower compared to the third alternative. The energy required to produce structural steel is the lowest in the second alternative, i.e., 95% less compared to the first and 82% less compared to the third. Comparing total amounts, the third alternative requires the least energy, 26% less compared to the first and 13% less compared to the second.

In the case of global warming potential emissions (Figure 13), the first alternative requires the lowest reinforcing steel, and therefore the CO_2 emissions produced by this material are the lowest, i.e., 47% lower compared to the second and 10% lower compared to the third alternative. The amount of CO_2 emitted during the production of structural steel is lowest in the second alternative, i.e., 95% less compared to the first and 82% less compared to the third alternative. The effect of concrete on increasing global warming potential is lowest in the first alternative, i.e., 45% less compared to the second and 36% less compared to the third. Comparing total amounts, the third alternative generated the least amount of CO_2, 7% less compared to the first and 17% less compared to the second.

The comparison of ozone depletion potentials depicted in Table 5 shows that the least amount of concrete needed for the first alternative, so the emissions of the ozone depleting substances are lowest for this alternative, i.e., 45% lower compared to the second and 36% lower compared to the third alternative. The usage of structural steel is the lowest in the second alternative that leads to fewer emissions of the ozone depleting substances for this alternative. The ozone depletion potentials for reinforcement steel are similar for all alternatives.

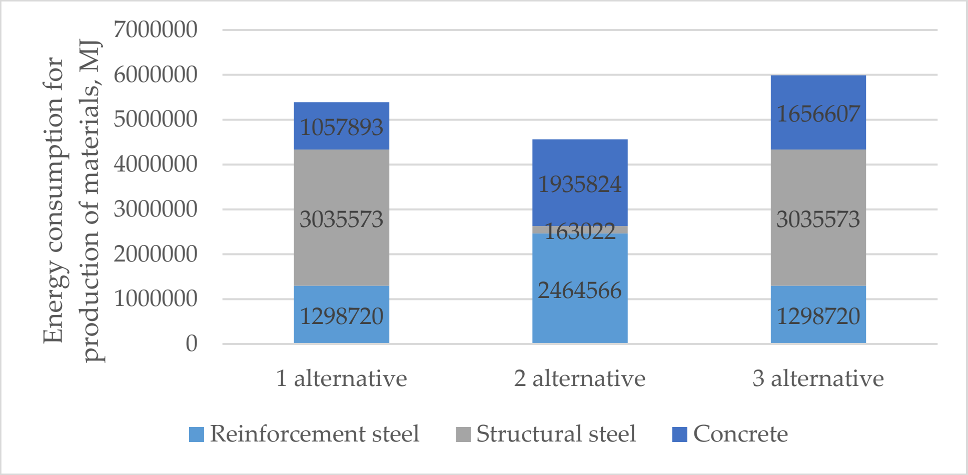


Figure 12. Comparison of energy consumption for production of materials (MJ).

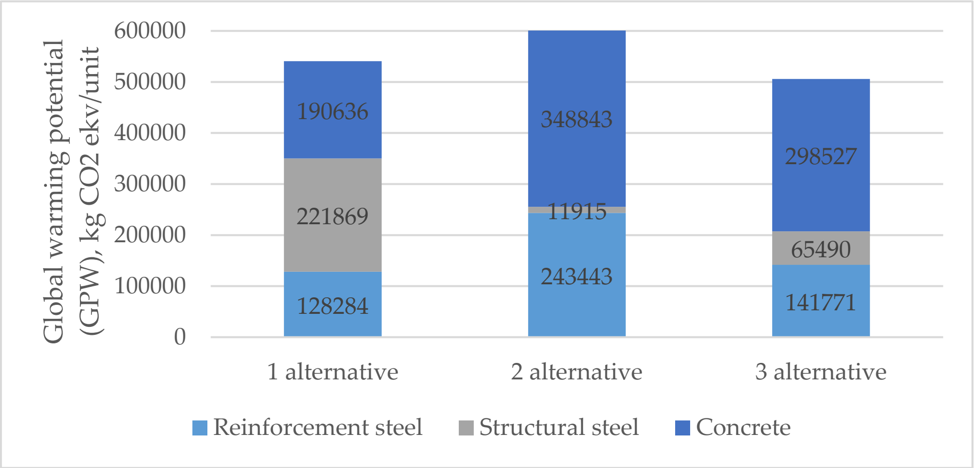


Figure 13. Comparison of global warming potentials (GWP, kg CO2 eq).

Table 5. Comparison of ozone depletion potentials (ODP, kg CFC-11 eq).

Alternatives	Reinforcement Steel	Structural Steel	Concrete
A1	2.04×10^{-5}	9.73×10^{-3}	5.57×10^{-3}
A2	3.87×10^{-5}	5.22×10^{-4}	1.02×10^{-2}
A3	2.26×10^{-5}	2.87×10^{-3}	8.72×10^{-3}

3.6. Multi-Criteria Analysis of Alternative Structural Solutions

The initial data for multi-criteria analysis depicted in Table 6 came from the computational analysis described in Sections 3.5.1–3.5.4.

Table 6. Initial data for multi-criteria analysis.

Criteria	Optimality Direction	A1	A2	A3	Criteria Weights
Physical criteria					
Total area, m^2	max	2862	2851	2853	-
1. Weight of structures, t	min	1951	3348	2896	**0.112**
2. Maximum load on columns in the peak load area, kN	min	1657	2623	1360	**0.093**
Economic criteria					
3. Costs of work, Eur	min	144,785	193,979	656,218	**0.098**
4. Costs of materials, Eur	min	1,641,433	1,240,115	1,197,778	**0.109**
Technological criteria					
5. Work amount, person-hours	min	2517	2687	12,159	**0.102**
6. Work amount, machine-hours	min	451	746	1487	**0.076**
Environmental criteria					
7. Energy consumption for production of materials, MJ	min	5,392,186	4,563,411	5,990,901	**0.130**
8. Global warming potential (GPW), kg CO_2 ekv/unit	min	540,789	604,201	505,788	**0.142**
9. Greenhouse gas emissions (CFC-11), kg CFC-11 eq	min	0.0153	0.0108	0.0116	**0.138**

The values of the criterion "Total area" are almost the same for all alternatives. Therefore, this criterion excluded by experts from the initial data matrix prepared for multi-criteria analysis.

The analysis of the initial data presented in Section 3.5 shows the manifold performance of alternatives. For example, according to the cost criterion, the second alternative wins compared to others. However, this alternative is losing in the assessment of environmental performance. The assessment and ranking of alternatives based only on expert opinion may be inaccurate and, therefore, must be verified. For the verification purpose, three multi-criteria decision-aiding methods were applied using the Formulas (1)–(20) presented in Section 2.4, Section 2.5 and Section 2.6.

Tables 7–9 present normalized-weighted criteria values and the results of intermediate calculations applying methods SAW, ARAS and COPRAS. Table 10 presents the aggregated results of the calculations and it shows that the first alternative wins in comparison to the other.

Table 7. Normalized-weighted criteria values r_{ij} and the criterion S_j of the weighted normalized values (SAW method).

Criteria	Alternatives		
	A1	A2	A3
r_1	0.113	0.066	0.076
r_2	0.076	0.048	0.092
r_3	0.097	0.072	0.021
r_4	0.079	0.104	0.108
r_5	0.102	0.096	0.021
r_6	0.075	0.045	0.023
r_7	0.113	0.133	0.101
r_8	0.133	0.119	0.142
r_9	0.097	0.138	0.128
S_j	0.884	0.821	0.713

Table 8. Normalized-weighted criteria values $\hat{x}_{ij}$, the values of optimality function S_i and the utility degree K_i of each alternative (ARAS method).

Criteria	**Alternatives**			
	A0	**A1**	**A2**	**A3**
$\hat{x}_1$	0.0501	0.0501	0.0292	0.0337
$\hat{x}_2$	0.0393	0.0323	0.0204	0.0393
$\hat{x}_3$	0.0493	0.0493	0.0368	0.0109
$\hat{x}_4$	0.0401	0.0292	0.0387	0.0401
$\hat{x}_5$	0.0476	0.0476	0.0446	0.0098
$\hat{x}_6$	0.0393	0.0393	0.0238	0.0119
$\hat{x}_7$	0.0510	0.0432	0.0510	0.0388
$\hat{x}_8$	0.0512	0.0479	0.0429	0.0512
$\hat{x}_9$	0.0523	0.0369	0.0523	0.0487
S_i	0.420	0.376	0.340	0.285
K_i	1.000	0.894	0.808	0.677

Table 9. Normalized-weighted criteria values d_{ij} and relative importance Q_j of each alternative (COPRAS method).

Criteria	**Alternatives**		
	A1	**A2**	**A3**
d_1	0.027	0.046	0.040
d_2	0.027	0.043	0.022
d_3	0.014	0.019	0.064
d_4	0.043	0.033	0.032
d_5	0.015	0.016	0.071
d_6	0.013	0.021	0.042
d_7	0.045	0.038	0.050
d_8	0.047	0.052	0.044
d_9	0.056	0.040	0.042
Q_{j}	0.379	0.362	0.273

Table 10. Results of multi-criteria analysis.

Methods		**A1**	**A2**	**A3**
SAW	S	0.884	0.821	0.713
ARAS	K	0.894	0.808	0.677
COPRAS	Q	0.379	0.362	0.273
Integrated		0.719	0.664	0.554
Rank	R	1	2	3

The results show that SAW and ARAS methods give similar values for the utility degrees of the optimality functions (S and K) for alternatives A1 and A2 (Figure 14). In the first case, the distance of A2 from A1 is approximately 7%. In the case of ARAS method, results for A3 and A1 differ in about 16%. According to COPRAS method, results for A3 and A1 differ by a quarter and this difference can be considered as significant. The reason for the difference between the rationalities of the alternatives could be the assumptions made at the beginning of the study and the preferences of decision-makers expressed in criteria weightings. In other cases, when decision-makers set different goals, the results could differ as well.

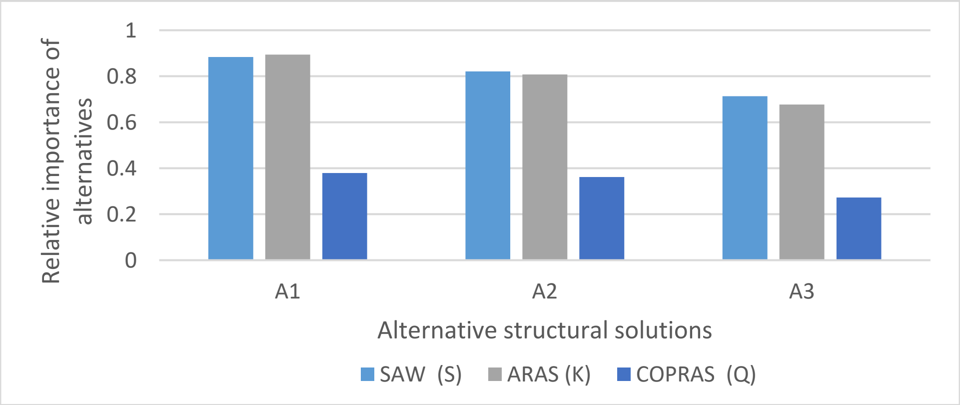


Figure 14. The comparison of the results of multi-criteria analysis.

4. Discussion and Conclusions

The proposed approach for sustainability analysis integrates the analysis of environmental, social, technological and economic factors. MCDA methods integrated into the approach ensure that the assessment is reliable. The study revealed that it is rational to use multi-criteria decision-aiding methods to assess the sustainability of alternative structural solutions at an early stage of building design. MCDA application allows the investor to better assess the attractiveness of alternatives. Multiple-criteria decision-aiding methods give the possibility to improve the decision-making process. By integrating three different utility functions represented in applied MCDA methods, we show the possibilities to enhance the robustness of decision-making. The proposed model is versatile, and therefore can be applied to different cases.

The results of the study show that the inclusion of environmentally friendly solutions will raise the cost of the project. For example, the third alternative is optimal in terms of energy consumption and environmental performance, but the cost of implementing this alternative will be 23% higher than that of the other alternatives, and construction work will take 79% longer than that of a rational alternative. More research is needed in the future to prove the results of this study.

The reported weaknesses of sustainability assessments led to the conclusion that there is a need for fast-in-application, simple and reliable methods to assess the sustainability of structural solutions at early design stages. The use of cloud-based BIM technologies that store “big data” should be considered to manage the sustainability of buildings. In the future, BIM—as a promising technology—should be promoted for environmental sustainability management throughout the life cycle of buildings.

The decision-making process in the selection of sustainable solutions on the early design stage requires utilizing additional techniques to optimize the assessment of many alternatives. Building Information Modelling (BIM) offers the possibility to assess different design alternatives at the conceptual stage of a project. BIM also helps structural designers select the right type of materials more easily during the early design stage. With the help of integrated tools, structural designers can assess environmental impacts throughout the building’s life cycle. However, there are some challenges related to data loss during data transfer from one software package to another (due to the low interoperability of software packages). This is the main limitation, and attempts must be made to solve this problem.

The case study revealed that the new BIM-based approach requires solutions that allow performing tasks on different software platforms that can operate in parallel or sequence. Future research will focus on developing a solution for the automated selection of the structural elements to form alternative bearing structures of building. More research is needed with a focus on developing a solution for better data exchange between the different software packages used in the assessment.

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