The Conceptual Model of the BIM4NZEB-DS System for Selecting Technological Variants of Rational Passive Energy Efficiency Measures for a Sustainable Building

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Abstract. Implementing sustainable solutions in building design is one of the significant elements in achieving the transition to sustainability. The diversity of structural elements, construction materials, and the various preferences of interested parties complicate the decision-making process. Building Information Modeling (BIM) provides a wide range of available technological solutions and methods for automated decision support and can make decision-making more efficient. This study presents the conceptual model for BIM4NZEB-DS system for the automated selection of rational variants of passive energy efficiency measures. The algorithm of this system will integrate the solutions for data transfer from the BIM model and multi-criteria methods for the analysis of variants. The assessment of variants is based on economic and environmental criteria. The purpose of the system is to increase the reliability of the assessment, optimise the technological and human resources required, and minimise the time of decision-making. The developed system will be validated using the BIM model of real-case building.
Keywords: *early design stage solutions; BIM; multi-criteria analysis; sustainability; BIM4NZEB-DS.*

Introduction

Relevance of the article

Building Information Modeling (BIM) allows us to solve the problems of sustainable design by modelling various elements of a building. However, BIM does not guarantee that the designer or building user chooses them rationally. Sustainability is a multifaceted phenomenon that includes a variety of sustainability categories, like environmental, social and economic issues. However, in the traditional approach of building design, architects and structural engineers rarely assess the environmental dimension, which has been recognised in the integrated building design approach as one of the most important factors (Hou, Li & Rezgui, 2015). The importance of multiple criteria in decision-making is sometimes underestimated, which also influences the added value of construction projects. The opportunities that give an integrated application of digital technologies, multifaceted approach and relevant assessment methods and tools will help to locate a transparent and reliable decision-making environment.

Level of problem investigation

The observation was made based on the review of recent scientific research in the field of digitalisation that there is an apparent lack of investigations focused on integrated solutions for decision-making in the early design stage of a building. Specifically, there is a lack of solutions that will enable the user to select rational technological variants in the BIM model based on multiple criteria.

Scientific problem

Sustainability is a manifold phenomenon that includes various categories of sustainability, such as environmental, social and economic issues. However, in traditional building design practice, architects and civil engineers rarely consider the environmental dimension, which today is recognised as one of the most important factors (Hou, Li, & Rezgui, 2015). A sustainable design includes not only compliance with building standards but also foresees the production of repetitive elements and mass production, which allows to reduce costs (Burgan & Sansom, 2006). To ensure the sustainability

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of the structural design, researchers also evaluate CO2 emissions and lifetime (Yepes, García-Segura, & Moreno-Jiménez, 2015). The assessment of the eco-efficiency of construction materials used for load-bearing structures has been made (Brown, & Mueller, 2016). Load-bearing structures have been compared using physical parameters, cost of construction and cost of materials, technological considerations, and environmental impact (Vilutienė, Kumetaitis, Kiaulakis, & Kalibatas, 2020). The academic community also recognised the potential of BIM in sustainable design (Liu, Lu, & Peh, 2019). BIM allows to solve sustainable design problems by modelling various building elements. However, BIM does not guarantee that they will be chosen rationally by the designer or building user. Unreliable decisions can have a negative impact on the sustainable development of cities. In addition, choosing a specific solution based on the requirements of the organisation requires finding a compromise between different categories (e.g. environmental, social and economic). The complexity of buildings and the need to evaluate many sustainability categories requires that reliable tools based on a robust optimisation algorithm should be used to select the optimal set of solutions.

Object of the article is the conceptual model of the BIM4NZEB-DS system for the automated selection of rational variants of passive energy efficiency measures.

Aim of the article is to compile a structure of the BIM4NZEB-DS system for the automated selection of rational variants of passive energy efficiency measures.

***Objectives of the article*:**

1. To analyse the research on the integration of multi-criteria analysis, BIM and sustainability criteria.
2. To select the initial set of criteria for the assessment of passive energy-saving measures.
3. To make considerations regarding the necessary functions of the BIM4NZEB-DS system and its components.

Methods of the article

This research is based on comprehensive literature review, analytical, numerical, and case study methods. Based on the literature analysis, the recent research on the integration of multi-criteria analysis, BIM and sustainability criteria was systematised, and the criteria for the assessment of passive energy-saving measures have been identified. The development of the BIM model examined in the case study was performed using modelling software tools.

1. Analysis of recent research on the integration of BIM, MCDM and sustainability issues

Sustainable building practices are highly debated and of great concern due to the increasing impact on environmental degradation and other aspects. Buildings consume about 25% of water, 55% of timber, and generate about 40% of waste (United Nations Environment Programme, 2020). In 2050 about 68% of society will live in cities that cover only 2% of the planet's surface, but consume 78% of energy and emit 60% of greenhouse gases (United Nations, 2019). The construction industry is responsible for a significant impact on the environment, consuming a large amount of natural resources worldwide and generating excessive construction waste (Jain, 2021; Gehlot & Shrivastava, 2021).

Growing environmental concerns, strict building regulations and the growing need to conserve natural energy are driving the demand for energy-efficient buildings. Recently, sustainability assessment initiatives have also been actively developed. The proposal for an EU Sustainability Reporting Directive (COM (2021)189) proposes that companies provide transparent and comparable information on the sustainability of their business practices as a basis for investment decisions. Market players will need to apply the requirements of this Directive and include sustainability criteria in their investment valuation models in order to contribute to the objectives of the Green Deal and to benefit from the financing and support mechanisms offered by the EU. This requirement is directly related to the planning, design, construction, and operation stages of the building life cycle. And it directly affects all players in the construction sector, from customers, designers, builders to users.

A distinctive feature of a sustainable building is its ability to significantly reduce environmental impact, energy consumption and greenhouse gas emissions throughout its life cycle (Kim & Yu, 2018). Applying sustainable building principles to the design process can improve the environmental performance of the construction industry. Since the energy-efficient and sustainable building solutions proposed at the design stage have a direct impact on the building's energy consumption and the building's environmental performance throughout its life cycle, making the right decisions at an early design stage is vital. Sustainability decisions are multi-objective, so it is appropriate to apply multi-criteria decision-making (MCDM) models (Huang, Zhang, Ren, Liao, Zavadskas, & Antuchevičienė, 2020). MCDM has demonstrated its ability to integrate technical information and multi-stakeholder objectives into decision-making. These methods allow the ranking of decision-making schemes by integrating conflicting indicators (Ishizaka, & Siraj, 2018).

The benefits of MCDM application can be revealed better when these methods are combined with BIM (Chen, & Pan, 2016). The solution of construction project tasks in an integrated way using BIM methodology and multi-criteria analysis methods has recently been discussed in many studies. The application of MCDM helps to overcome the limitations of BIM in multi-objective optimisation (Elaheh, Vadiee, & Johansson, 2019). With the development of construction technologies the complexity of projects and information requiring integration has also increased. BIM is expected to replace the traditional information management process and make possible the horizontal integration between different stakeholders and the vertical integration of information at different stages (Elonen, & Artto, 2003). BIM tools provide opportunities to integrate the fragmented architectural, engineering and construction parts of the project (Chang, & Shih, 2013); include in the model both geometric and non-geometric data (Singh, Gu, & Wang, 2011); by integrating data from different disciplines can quickly and accurately extract information from components and aid in evaluation (Staub-French, Fischer, Kunz, & Paulson, 2003). However, how to integrate and use building information to facilitate decision-making is still under discussion.

2. Steps of the development of a conceptual model of the BIM4NZEB-DS system

The analysis and research included the following steps:

Step 1. Analysis of literature on the integration of multi-criteria analysis, BIM and sustainability criteria. This step aims to examine the existing scientific papers and determine the situation and gaps in the integrated application of BIM, MCDM and sustainability criteria. The main research question in this step is "What are the main indicators used in the assessment of sustainable design and construction solutions?"

Step 2. Selection of sustainability criteria and methods to obtain their values. Based on literature analysis the initial set of sustainability criteria was selected. In this step, the final set of criteria and methods to obtain their values were considered by experts during the Delphi study. The assumptions were made regarding the data gathering and data sources.

Step 3. Development of a structure of the system (BIM4NZEB-DS) for the automated selection of rational variants of passive energy efficiency measures. In this step, considerations were made regarding the necessary functions and components of the BIM4NZEB-DS system.

3. Expert assessment of sustainability indicators and functions of the BIM4NZEB-DS system

Economic, social and environmental indicators are usually applied to the assessments of energy efficiency and sustainability in construction projects. There are also technological and structural parameters that are evaluated as additional criteria depending on the research objectives. The group of economic indicators often include design cost, construction cost, material cost, and payback period (Gorgolewski, Grindley, & Probert, 1996; Zavadskas, & Antucheviciene, 2007; Sun et al., 2019; Dipasquale, 2019). As technological indicators considered: human labour cost (Shehata, & El-Gohary, 2012), efficiency and utilisation of heating devices (Mardiana-Idayu, & Riffat, 2012; Willem, Lin, & Lekov, 2017), efficiency and utilisation of ventilation systems (Giama, 2022). Solutions considered in the assessment of design: the orientation of the building with respect to the direction of north (Karimimoshaver, & Shahrak, 2022), compactness of the building (optimal ratio of external partitions and heated space) (Wang, Liu, & Zhang, 2021; Kistelegdi, Horváth, Storcz, & Ercsey, 2022), thermal insulation properties of partitions (Bojic, Yik, Wan, & Burnett, 2002;

Asdrubali, D'Alessandro, & Schiavoni, 2015; Karimimoshaver, & Shahrak, 2022), air circulation and indoor air quality (Xu, F., Xu, S., Passe, & Ganapathysubramanian, 2021), airtightness of the building (Zheng, Long, Cheng, Yang, & Jia, 2022). However, the greatest importance is given to environmental indicators, such as primary energy consumption (Jie, Zhang, Fang, Wang, & Zhao, 2018, Maslesa, Jensen, & Birkved, 2018), greenhouse gas emissions (Pervez, Ali, & Petrillo, 2021; Kongboon, Gheewala, & Sampattagul, 2022), indicators for assessing the generation of waste (Yuan, 2013; Solís-Guzmán et al., 2009; Lu, Webster, Chen, Zhang, & Chen, 2017).

The study was limited to the analysis of passive energy-saving measures. Passive energy-saving measures include external wall construction with thermal insulation, roof construction with thermal insulation, energy-efficient windows and the use of modular and more sustainable materials. Experts through the three-round Delphi study, based on literature analysis, proposed the initial set of criteria (Table 1) for the assessment of passive energy-saving measures. Ten experts of experienced and knowledgeable people from companies with BIM-related activities and academic institutions were selected for the panel. The set contains the most frequently used, from the environmental point of view the most important indicators. Deciding on the parameters for the sustainability assessment one of the criteria for the selection was the existence of a reliable and objective source of data. In order to declare the environmental parameters of products, manufacturers prepare EPD declarations in accordance with the requirements of the EN 15804:2012+A2:2019 standard, which ensures data reliability and comparability. In addition to the selected environmental indicators, the price of alternative solutions was considered as the basis for the assessment of the economic feasibility of a solution. The cumulative energy demand (CED) determines the impact on the environment and is mentioned as one of the key indicators in literature sources, and was also included in the selected set of indicators.

Table 1

Sustainability indicators determined by experts for the assessment of wall details

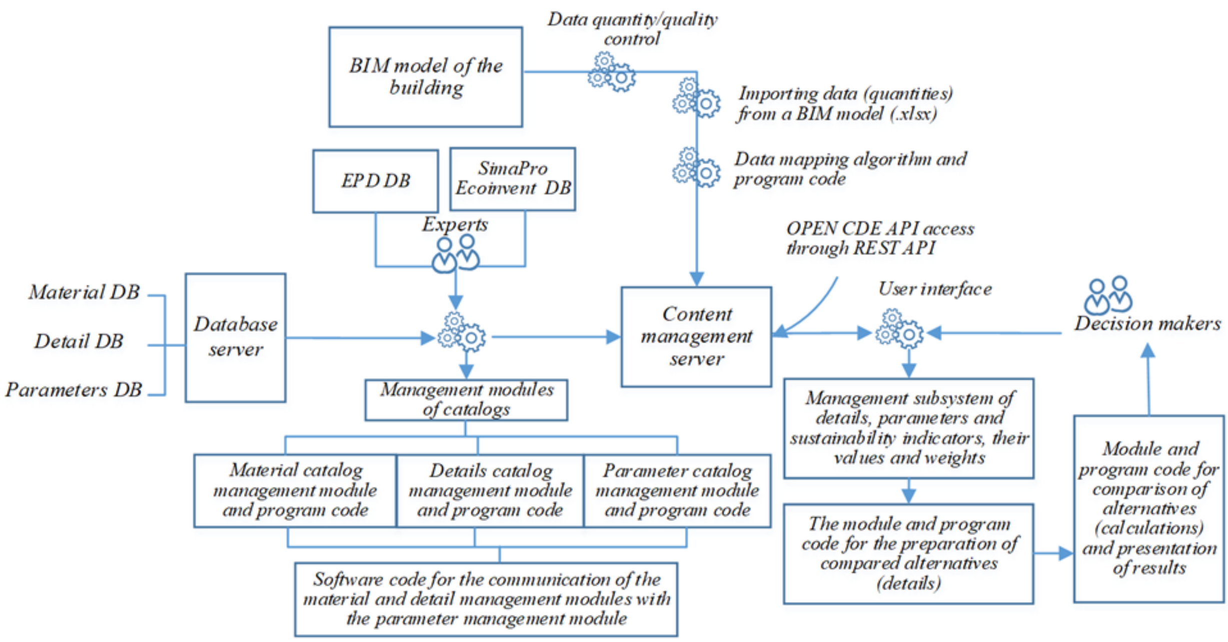
Indicators	Abbreviation	Measuring units	Optimisation direction	Weights
Construction cost	C	euro/(m2, m3, unit)	min	0.30
Cumulative energy demand	CED	MJ/(m2, m3, kg)	min	0.05
Global warming potential	GWP	kg CO2 eq	min	0.10
Ozone layer depletion potential	ODP	kg CFC-11 eq	min	0.10
Acidification potential	AP	H+ moles eq	min	0.05
Eutrophication potential of fresh water	EP	kg P eq.	min	0.05
Formation potential of tropospheric ozone	POCP	kg NMVOC eq.	min	0.05
Abiotic depletion for fossil resources potential	ADP	MJ	min	0.05
Amount of construction waste	CW	%	min	0.10
Amount of demolition waste	DW	%	min	0.05
System thickness	t	mm	min	0.05
Thermal resistance of a system	R	m^2K/W	max	0.05

Source: created by the authors.

During the Delphi study, experts decided on the methods to be used for the calculation of environmental impact indicators and calculation of construction waste. For the calculations of environmental impact indicators was decided to use SimaPro (v9.3.0.3) software. This software uses different environmental impact methods (models) that can be applied to determine individual impact indicators. Cumulative energy demand (non-renewable) indicators calculated using CED v1.08 method, Global warming potential and Ozone layer depletion potential indicators – IMPACT 2002+ v2.1, Acidification potential indicators – TRACI 2 v3.03, Eutrophication potential and Formation potential of tropospheric ozone indicators – ReCiPe Midpoint (E) v1.05, Abiotic depletion for fossil resources potential indicators – Eco-indicator 99 (H) v2.08. Pollution parameters per unit quantity for environmental indicators can be obtained from the product EPD declaration database (https://www.environdec.com/home) if EPDs have been prepared. To identify expected waste quantities the method described by Solís-Guzmán et al. (2009) was proposed to use. Quantities of elements necessary for the calculation of environmental indicators, thickness of elements and data necessary to calculate the thermal resistance of a system come from the BIM model.

The main considerations made in the third step of research include the necessary functions and components of the BIM4NZEB-DS system, solutions for extraction of data from the BIM model, extracted data analysis and information structure optimisation, including classification of passive energy efficiency measures.

The purpose of BIM4NZEB-DS system is to enable the user to select rational technological variants of passive energy-saving measures based on the principles of sustainable design and construction. The assessment of technological variants must be made using multi-criteria decision-making methods. Therefore, a system algorithm must be developed based on them and must enable calculations and ranking of variants of the building's compatible sets of elements. The assessment of variants is based on economic and environmental criteria determined by experts. The system must increase the reliability of the assessment, optimise the necessary technological and human resources, and shorten the time spent on the assessment. Taking into account the purpose of the system and the functions it must perform, the necessary elements and their interrelationships are identified and presented in a conceptual model (Fig. 1).



Source: created by the authors

Fig. 1. The conceptual model of the BIM4NZEB-DS system

The system development will be performed by combining databases and several subsystems with specially designed interfaces. All algorithms and logic of calculations will be executed only in the server part (backend), thus separating rendering and processing mechanisms. Integration and testing will be carried out with the Web system BIMGates.lt, which is developed for construction price estimates.

An evolutionary prototyping method will be used for the development of the BIM4NZEB-DS system prototype. In this method, prototype elements (subsystems) are development, delivery and improvement of steps ("sprints") over many stages until the final version of the prototype is created. The user can experiment with the results (subsystems) presented while others are being created.

Conclusions

1. The analysis of the research on the integration of multi-criteria analysis, BIM and sustainability criteria was made to determine gaps in the integrated application of BIM, MCDM and sustainability criteria and to answer the question on the main indicators used in the assessment of sustainable design and construction solutions.

2. The original set of sustainability assessment criteria proposed (including economic and environmental criteria), allows the user of the system to select rational sustainable building solutions. Taking into account the goals of the decision maker in evaluating the building's passive energy efficiency measures, the system algorithm will allow the selection of relevant sustainability indicators from the set provided by experts.
3. The conceptual model of the BIM4NZEB-DS system was proposed and the main functions and components were considered. In the first testing stage, the prototype of the proposed system will include elements of the building envelope, i.e. the walls, roof, windows, doors, and foundation. In future research, the prototype will include the active engineering systems and the solutions for the possible integration of passive and active measures in a single assessment.

The findings can be interesting to all participants of the integrated construction project team who deliver the solutions and make decisions throughout the construction project life cycle on the concept, design, construction and building operation stages.

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