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MULTI-CRITERIA EVALUATION OF MASONRY FACADE INSTALLATION BY SAVING RESOURCES AND LIMITING WASTE

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Abstract. The aim of the study is to offer a new sustainable method for production and installation of masonry facade. The paper presents a case study of facade reconstruction and aims to evaluate three masonry facade alternatives according to multiple criteria, focusing on saving resources and limiting waste. Building Information Model was prepared for precise quantity surveying and management. The Entropy method was applied to determine the relative weights of criteria, and alternatives were evaluated and ranked by applying the CoCoSo (Combined Compromise Solution) method. Prefabricated tension masonry panels were found to be the best sustainable way of masonry facade installation.

Keywords: sustainable development, waste management, masonry facade, BIM, MCDM, CoCoSo.

Introduction

Waste is serious issue in construction industry and needs big efforts to reduce it using waste management tools at all stages of project implementation such as plan, design, construction, maintenance, refurbishment and demolition. Sustainable waste management approach needs application of numerous techniques and digital technologies for effective information management of whole project life cycle starting from project aims, design tasks, construction guidance to low emission maintenance and full recyclability.

Masonry bricks are popular facade material not only in Europe, but also in all-world, moreover their annual consumption is very high. The several million tons of construction waste are generated during construction stage every year and one of the main wastes are bricks (Wong et al., 2018). This is a serious problem for the sustainable development of masonry facades. Vandervaeren et al. (2019) determine that masonry facade is efficient as environmentally friendly material and can be reused and properly recycled at the end-of-life cycle. Moreover, Lesniak and Balicki (2016) determine that brickwork is suitable solution for a commercial building facade, such facade has high durability, needs less maintenance and it has high resistance for freeze-thaw cycles, fire and other weather conditions. Also, Tam et al. (2018) investigated the cost-effectiveness of the eleven facade systems by determining life cycle costs over 20 years and determined that masonry facades are most economical, despite initial material price is high.

However, traditional masonry facade and other construction design methods are not sufficient to optimize the production stage for sustainable waste management during project life cycle. Some effective construction waste management solutions can be implemented using prefabricated products together with Life Cycle Assessment (LCA) and Building Information Modelling (BIM) for quantity calculations for further sustainability evaluation of typical reinforced concrete frame structural buildings (Cheng et al., 2022). Also, it can be used to make analysis of concrete and drywall construction waste calculation with BIM tools (Guerra et al., 2020). Other authors analyse the BIM software tools to reduce the construction/demolition wastes and precise estimation (Akinade et al., 2018; Shi & Xu, 2021). It is complicated to have same level BIM competencies of project participants in different stages, but sometimes it is necessary for implementing waste-efficient building projects with deep sustainable approach in project management, procurement, design and construction. In these cases, identification of BIM expectations (Akinade et al., 2018) and BIM competences (Ganiyu et al., 2020) both company and industry/country level are crucial for waste-efficient BIM project success or can make great obstacles for BIM adoption.

During the design stage it is possible to use building information modelling and parametric design to ensure

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optimisation of floor tiles layout, supports prefabrication, cost reduction (Wu et al., 2022) and reduce material waste during the construction stage (Eldeep et al., 2022), but at the end risk indicators must be evaluated to foresee delivery and installation uncertainties.

Countries trying to implement sustainable approach and BIM for building refurbishment (Migilinskas et al., 2017) and demolition (Nikmehr et al., 2021; Schamne et al., 2022), but it still generates uncertain big volumes of construction and demolition wastes. In one of the examples made by Jiang et al. (2022), BIM models of the existing old road and its surrounding buildings were created, after the BIM models of the new road and engineering systems were designed. Finally, based on the BIM models and using clash detection selection of road components was made with road engineering systems and assistance for building demolition. Other example can be an application of Image-to-BIM scanning technologies that can increase the accuracy of automatic demolition waste calculation both internal and external constructions. Some researchers manged to use collected digital data and combined BIM model to improve cost, time, waste and safety management (Hu et al., 2022).

Various MCDM (Multiple Criteria Decision Making) techniques are used in combination with BIM for different problems. It is already clear that MCDM plays an important role in digitizing the AEC (Architecture, Engineering and Construction) industry. Pavlovskis et al. (2017) suggested to adjust criteria system to determine the reasonable reconstruction alternative of a building using WASPAS-G (Weighted Aggregated Sum Product Assessment) method with grey attributes scores. Migilinskas et al. (2017) presented the evaluation of BIM application and MCDM in reconstruction projects. Fazeli et al. (2019) proposed a methodology to integrate BIM and decision-making method Fuzzy TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) to effectively optimize the selection of sustainable building components based on the conceptual design for the construction project phase. Jalilzadehazhari et al. (2019) applied the integration of BIM and AHP (Analytic Hierarchy Process) as a multi-criteria decision-making method for reducing building energy consumption and improving indoor comfort. Migiliniskas et al. (2016) suggested to use BIM, MCDM and energy simulation tools for integrated building design. Wang et al. (2017) proposed a supplier selection system that is adapted to efficiently integrate supply chain management information. The proposed selection system works by integrating building information modelling (BIM) and geographic information systems GIS (Geographic Information System).

Therefore, this paper proposes a new prefabricated installation of masonry facade, as prefabricated works are considered a sustainable construction technology that reduces the various construction waste (Cheng et al., 2022). The aim of the paper is to present a new sustainable approach of production for suspend brickwork facade installation at the production stage for a reconstruction of the brickwork facade of the Wroblewski Library of the Lithuanian Academy of Sciences. In the paper standard methods installation of masonry support for brickwork, brickwork lintel, installation masonry support, stainless-steel lintels covered with brick tiles are analysed and in addition it is suggested sustainable production of prefabricated tension brickwork panels. The methods of production of brickwork suspend support are analysed according to BIM and MCDM. The criteria for evaluating three alternatives through saving resources and limiting waste at the production stage are suggested. The Entropy method is used to determine the relative weights of criteria. Next, BIM model prepared for precise quantity survey and management. Finally, CoCoSo (Combined Compromise Solution) method is applied for multiple criteria evaluation of alternative production methods.

The remainder of this study is as follows: methodology is presented in Section 1, the research case study, including description of analysed alternatives and evaluation criteria as well as calculation results are presented in Section 2, and the final Section is related to the conclusions of the research.

1. Methodology

The steps of suggested approach for multi-criteria evaluation of alternative brickwork facade installation methods at the production stage are listed below:

Step 1. Defining criteria for evaluating alternatives through saving resources and reducing waste at the production stage.

Step 2. Applying the Entropy method to determine the relative weights of the criteria.

Step 3. Preparing Building Information Model for precise quantity survey and management.

Step 4. Evaluating and ranking the alternatives using the multi-criteria CoCoSo method.

1.1. The Entropy method

The Entropy method is derived from information theory presented by Shannon in a middle of previous century (Shannon, 1948). The properties of the method and its benefits over other criteria weighting methods were revealed by Chen (2020), Kumar et al. (2021).

The calculation process is briefly presented below.

Initial criteria values x_{ij} are transformed into normalized values $\overline{x}_{ij}$, $i = 1, \ldots, m$, $j = 1, \ldots, n$, m – number of alternatives, n – number of criteria. Then p_{ij} values are calculated:

$$p_{ij} = \frac{\overline{x}_{ij}}{\sum_{i=1}^{m} \overline{x}_{ij}}. \tag{1}$$

The values of the information entropy of the j-th criterion E_j are calculated:

$$E_j = -k\sum_{j=1}^{n} p_{ij} \ln p_{ij}, \quad (2)$$

where $k = 1/\ln m$.

The degrees of divergence d_j are computed:

$$d_j = 1 - E_j. \quad (3)$$

Finally, the criteria weights w_j are calculated:

$$w_j = \frac{d_j}{\sum_{j=1}^{n} d_j}. \quad (4)$$

1.2. The CoCoSo method

This is a rather new method, developed by Yazdani et al. (2019). The method is able to identify differences between alternatives and rank them, even if alternative solutions are close in criteria values. It was successfully applied for investigation the environmental impacts of construction projects (Banihashemi et al., 2021).

The calculation steps are as below.

Initial criteria values x_{ij}, $i = 1, \dots, m$, $j = 1, \dots, n$, m – number of alternatives, n – number of criteria, are transformed into normalized values r_{ij} by using different equations for benefit criteria (Eq. (5)) and for cost criteria (Eq. (6)):

$$r_{ij} = \frac{x_{ij} - x^{\min}}{x_i^{\max} - x_i^{\min}}; \quad (5)$$

$$r_{ij} = \frac{x^{\max} - x_{ij}}{x_i^{\max} - x_i^{\min}}. \quad (6)$$

Weighted sum S_i (Eq. (7)) and weighted product P_i (Eq. (8)) values are calculated:

$$S_i = \sum_{j=1}^{n} r_{ij} w_j; \quad (7)$$

$$P_i = \sum_{j=1}^{n} r_{ij}^{w_j}. \quad (8)$$

Three strategies are used for evaluating the alternatives (Eqns (9), (10) and (11)) and the final ranking k_i is determined by Eq. (12):

$$k_{ia} = \frac{P_i + S_i}{\sum_{i=1}^{m} (P_i + S_i)}; \quad (9)$$

$$k_{ib} = \frac{S_i}{\min_i (S_i)} + \frac{P_i}{\min_i (P_i)}; \quad (10)$$

$$k_{ic} = \frac{(1-\lambda)P_i + \lambda S_i}{(1-\lambda)\max_i (P_i) + \lambda \max_i (S_i)}, \quad 0 \le \lambda \le 1; \quad (11)$$

$$k_i = (k_{ia} k_{ib} k_{ic})^{\frac{1}{3}} + \frac{1}{3}(k_{ia} + k_{ib} + k_{ic}). \quad (12)$$

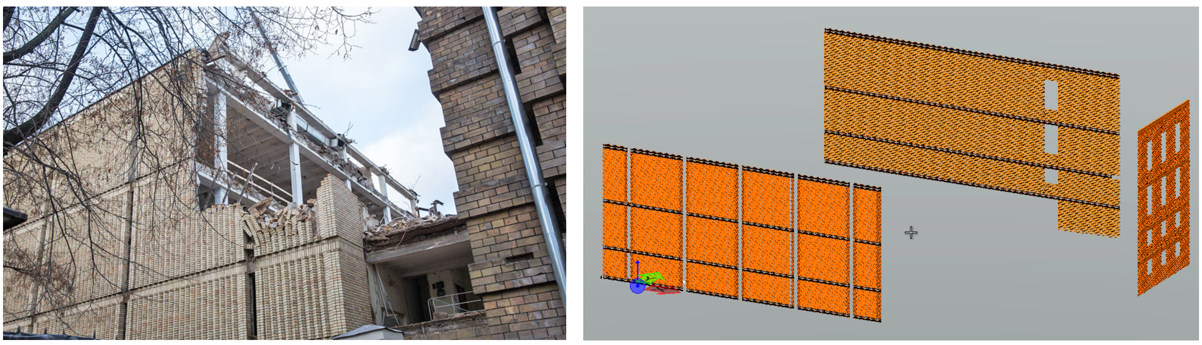
2. Case study

The case study of the Wroblewski Library of the Lithuanian Academy of Sciences is presented in this section. The building is in an emergency condition, therefore, according to the project, the main structures of the building are strengthened, and masonry facade is reconstructed. BIM was applied for calculation of waste quantity from masonry facade of the Wroblewski Library (see Figure 1). Valuable features of masonry facade are distinguished, and three possible reconstruction alternatives are suggested. Criteria system for evaluation of alternatives, consisting of ten criteria, is prepared. The criteria, the alternatives and the calculation results applying the suggested methodology as presented in Chapter 1, are further described in Subchapters 2.1. and 2.2.

2.1. Alternatives and criteria

Alternative No. 1. Installation of masonry support for brickwork and brickwork lintel. Masonry support brackets are made of stainless steel, brackets are mounted to the reinforced concrete structure. Every masonry facade fragment is supported by a row of suspend brackets.

Alternative No. 2. Installation of masonry support for brickwork and stainless-steel lintels covered with brick tiles. Every masonry facade fragment is supported by a row of suspend brackets as in alternative No. 1. but the brickwork lintels are prefabricated at the production stage.



a) b)

Figure 1. Demolition works of masonry facade: a) real demolition; b) BIM for waste quantities

Alternative No. 3 Installation of suggested sustainable prefabricated masonry panel. The masonry panels are reinforced and prefabricated at the production stage.

As the aim of the paper is to promote a new sustainable approach for suspend brickwork facade installation for a masonry facade reconstruction by analysing the three above-described possible facade installation alternatives through saving resources and reducing waste, criteria for evaluating the alternatives by saving resources and limiting waste at the production stage are presented and described in Table 1.

2.2. Calculation results applying Entropy and CoCoSo methods

The initial decision-making matrix including initial criteria values describing the alternatives is presented in Table 2. Relative weights of criteria w_j are determined by applying the Entropy method (Eqns (1-4)), and they are also presented in Table 2.

Then the CoCoSo method is applied. Initial criteria values are transformed into normalized values (Eqns (5) and (6)), then weighted sum and weighted product values are calculated (Eqns (7) and (8)). Three strategies are used for evaluating the alternatives (Eqns (9), (10) and (11)) and the final ranking k_i is determined by Eq. (12). The final evaluation and ranking of alternatives are provided in Table 3.

Table 3. Ranking alternatives by the CoCoSo method

	k_{ia}	k_{ib}	k_{ic}	k_i	Rank
Alternative No. 1	0.337	2.074	0.974	1.356	3
Alternative No. 2	0.345	2.105	0.997	1.391	2
Alternative No. 3	0.801	2.039	0.914	1.750	1

Table 1. Criteria description

Notation	Criteria	Optimization direction	Description
X_1	Steel weight, kg	min	The total steel weight of masonry facade support system. The criterion represents the ability to save resources.
X_2	Volume of masonry bricks, m^3	min	The volume of masonry brick for every alternative represents the amount of bricks for facade. The criterion represents the ability to save resources.
X_3	Reuse of metal fixing parts, %	max	Reuse of metal fixing parts for masonry facade installation. The criterion represents both the ability to save resources and to limit waste.
X_4	Steel waste, %	min	The criterion represents the ability to reduce waste in CNC laser cutting of steel fixing elements for masonry facade.
X_5	Remaking time of load-bearing metal elements, h	min	Remaking time of load-bearing metal elements, including masonry work for alternative options. The criterion represents the ability to save resources and reduce waste.
X_6	Energy consumption according to the number of reworked elements, kW/h	min	Energy consumption according to the number of reworked fixing elements of masonry facade. The criterion represents the ability to save resources.
X_7	Amount of steel elements from one steel sheet, %	max	Metal elements ratio of fixing elements for masonry facade from one steel sheet for every alternative. The criterion represents the ability to save resources and limit waste.
X_8	Supply costs, Eur	min	Supply costs of fixing elements for masonry façade to the project site. The criterion represents the ability to save resources.
X_9	Loading time, h/m^2	min	Loading time of fixing elements for masonry facade of every alternative for the m^2 of the project. The criterion represents the ability to save resources.
X_{10}	Waste removal price, Eur	min	Waste removal price after installation work. The criterion represents the ability to save resources and reduce waste.

Table 2. Initial decision-making matrix

Criteria	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}
Optimisation	min	min	max	min	min	min	max	min	min	min
Weight w_j	0.006	0.002	0.111	0.129	0.139	0.135	0.089	0.131	0.124	0.128
Alternative No. 1	3971.69	114.23	44.54	24.10	244.00	38.50	75.90	266.20	3.00	85.50
Alternative No. 2	7592.94	111.89	43.68	19.80	366.00	47.30	78.50	312.50	3.50	75.88
Alternative No. 3	3852.15	77.50	90.91	15.20	576.00	24.80	74.20	798.78	9.03	11.70

Calculation results show that usual installation methods are evaluated worse compared to the presented new method. The first alternative – installation of masonry support for brickwork and brickwork lintel – acquired the third rank. Secondly ranked alternative is installation of masonry support for brickwork and stainless-steel lintels covered with brick tiles. The third alternative – installation of suggested sustainable prefabricated masonry panel, is over 20 percent better than the previous ones and it takes the best rating according to criteria by saving resources and limiting waste at the production stage.

Conclusions

Based on the production approaches, the authors used BIM technologies for precise calculation of waste quantities and compared three possible methods of installation masonry facades at the production stage. It was suggested to apply a new sustainable method of production for masonry facade installation of sustainable prefabricated masonry panel (alternative No. 3) and compare it with regular production process of alternative No. 1 and alternative No. 2 applying multiple-criteria evaluation.

To evaluate the masonry alternative of facades installation methods a criteria system was proposed through saving resources and limiting waste at the production stage (by using the Entropy method to determine the relative importance of the criteria). According to the Entropy method X_1 steel weight ($w_j = 0.006$), X_2 volume of masonry bricks ($w_j = 0.002$) are less important and X_5 remaking time of load-bearing metal elements ($w_j = 0.139$), X_6 energy consumption according to the number of reworked elements ($w_j = 0.135$) and X_8 supply costs ($w_j = 0.131$) are the most important. According to final calculations applying CoCoSo method for ranking of alternatives and considering the weighted criteria, the alternative No. 1 gained the third rank. Alternative No. 2 is ranked second, 2.6 percent less than the alternative No. 1. Finally, it was found that the alternative No. 3 – prefabricated tension masonry panel, is the best sustainable method of masonry facade installation and waste management, it is ranked 20.5 percent better than Alternative No. 2.

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