Selection of Exterior Wall System and MCDM Derived Decision

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Abstract

In the field of construction practice, decisions regarding material selection frequently come down to a choice based on tradition, i.e. recommendations based on the experience of the engineers hired by an employer as designers, contractors, or energy efficiency engineers.

In the presented research, in addition to the Employer, technical individuals were involved in the decision-making process. The harmonisation of Employer opinions and those of experts were obtained through NGT technique and Delphi based method, due to the fact that different criteria for a decision could represent a field of interest of an individual participant in the process. The result was determining the criteria, their strictness, and their weighted effect.

As multi-criteria decision analysis has evolved into a powerful tool that assists decision-makers in generating "a cut above" choice in resolving specific cases and overcoming certain problems in the architectural and construction industry, the use of the MCDM method EDAS+ in the research ensured an exterior wall system ranking that was not influenced by experience or marketing.

Without intending to favour any manufacturer of building materials, the research presents eight exterior wall systems belonging to different categories of core materials, all with individual features, similarities, and differences.

When compared to otherwise arbitrary estimates or recommendations based on experience and the most commonly used building materials, the application of multi-criteria decision analysis in the case of exterior wall system selection for a particular 1938 Belgrade building generated more relevant selection results.

1 INTRODUCTION

The construction industry has developed significantly as it has taken into account conflicting, immeasurable, and experientially determined decision-making criteria. Environmental and social aspects are becoming more important and their proper synergy with economic aspects is the cornerstone for success in any construction business or procedure.

When facing a wide range of options in resolving specific cases and overcoming certain problems in the architectural – construction industry, multi-criteria decision making and analysis have become powerful tools that help decision-makers to generate "a cut above" choice. These tools are much more than simply a collection of theories, methodologies, and procedures; they are a distinct approach in dealing with decision problems (Greco et al., 2016). The evolution in the use of multi-criteria decision analysis techniques clearly shows an increased level of confidence in their assistance in the decision-making process (Jato-Espino et al., 2014). Multi-criteria decision-making methods are not only comprehensive, but also well-known instruments that are used for resolving decision-making dilemmas in architecture, construction, urban planning, and energy efficiency projects. As shown in territorial delimitation presented in articles by Ogrodnik (2019) and Bruen (2021), Asia, North America, and Europe (notably Poland and Lithuania, followed by Italy, Spain, Czech Republic, and France) are the leading study hubs on the topic of multi-criteria decision-making in architecture and civil engineering. In the aforementioned articles, researched authors used wide range of different methods, i.e.: AHP, ANP, CBA, COPRAS, CRITIC, (...), TODIM, TOPSIS and VIKOR. According to Ogrodnik's (2019) survey of the literature, MCDM approaches enable the deconstruction of different decision problems, increase the transparency of decision processes, allow the comparison of various decision alternatives, and reveal their strengths and shortcomings. (De Toro & Iodice, 2016; Šiožinyte & Antuchevičienė, 2013).

At the moment, there are no clear guidelines on how to choose the optimal exterior wall system or structural wall, which meets all the required criteria set by various intertwining disciplines. The question of how to make a more relevant selection of an exterior wall system arises when decisions about material selection frequently come down to a choice based on tradition, and recommendations based on the experience of the engineers hired by an employer as designers, contractors, or energy efficiency engineers. Construction and energy efficiency standards in different countries establish minimum requirements (Pérez-Lombard et al., 2009), but the design process should not be reduced to choosing the best alternative solely in terms of standards and initial design requirements. When Terms of Reference cannot be accomplished all at once it is necessary for the designer to define project objectives first and then limitations (Moghtadernejad et al., 2018).

The aim of the research study is the selection of a contact façade alternative (exterior wall system) in the specific case presented in this paper – the extension of a three-storey over ground downtown Belgrade (Serbia) building dating from 1938 by adding two more floors (Figure 1).
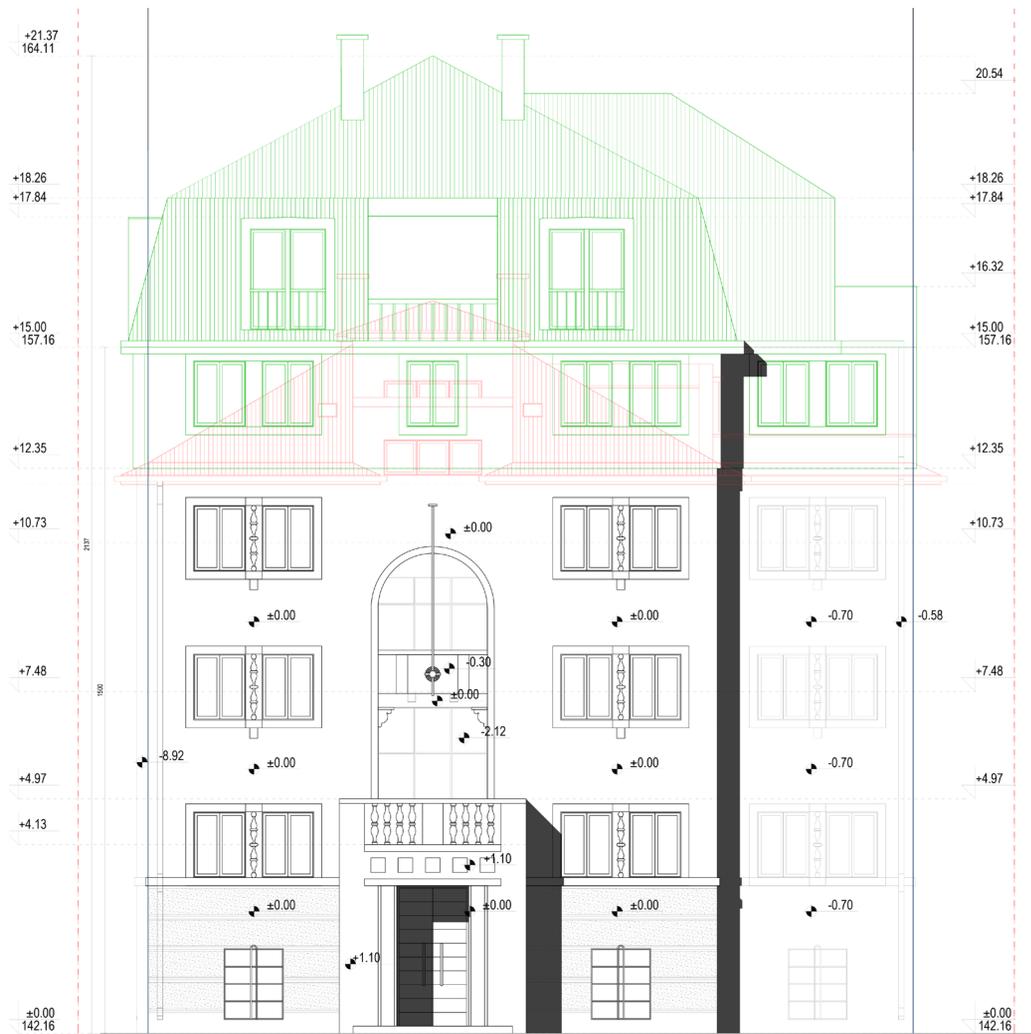
FIG. 1 Existing building and planned extension overlapped, Author's drawing based on Archive design, on-site measurements and planned extension

Since certain criteria could be in seemingly direct contradiction, for example the cost of construction compared to that of energy-efficiency, the success of such choices will not be reflected in maximising each of the criteria (Moghtadernejad et al., 2020). For these reasons, finding a balance between the criteria will be a requirement that must be met for the selection to be adequate. In the specific case presented in this paper, design teams must consider a wide range of options during the early phases of a project, both materials (exterior wall systems) and the process of their selection, in order to select those that best address the project constraints and objectives (Donato et al., 2017). Therefore, it is necessary to conduct a series of reviews and actions in order to find the optimal solution. Otherwise – in the building permit project and construction phase, the design would be modified through unnecessary, time-consuming and costly changes (Moghtadernejad et al., 2019).

The objective of the research is to provide a systematic decision-making process for selecting an exterior wall system that may be utilized in both particular project and future extension projects of the same multi-family building typology.

2 METHODOLOGY

The paper aims to provide a selection of exterior wall systems that can be used in the project, for the extension building permit and detailed design of the specific multi-family building typology.

The methodology was developed in the context of the selection of the exterior wall system, as a part of the thermal envelope of a multi-family residential building at a geographically determined location, through the application of the multi-criteria decision-making method (MCDM).
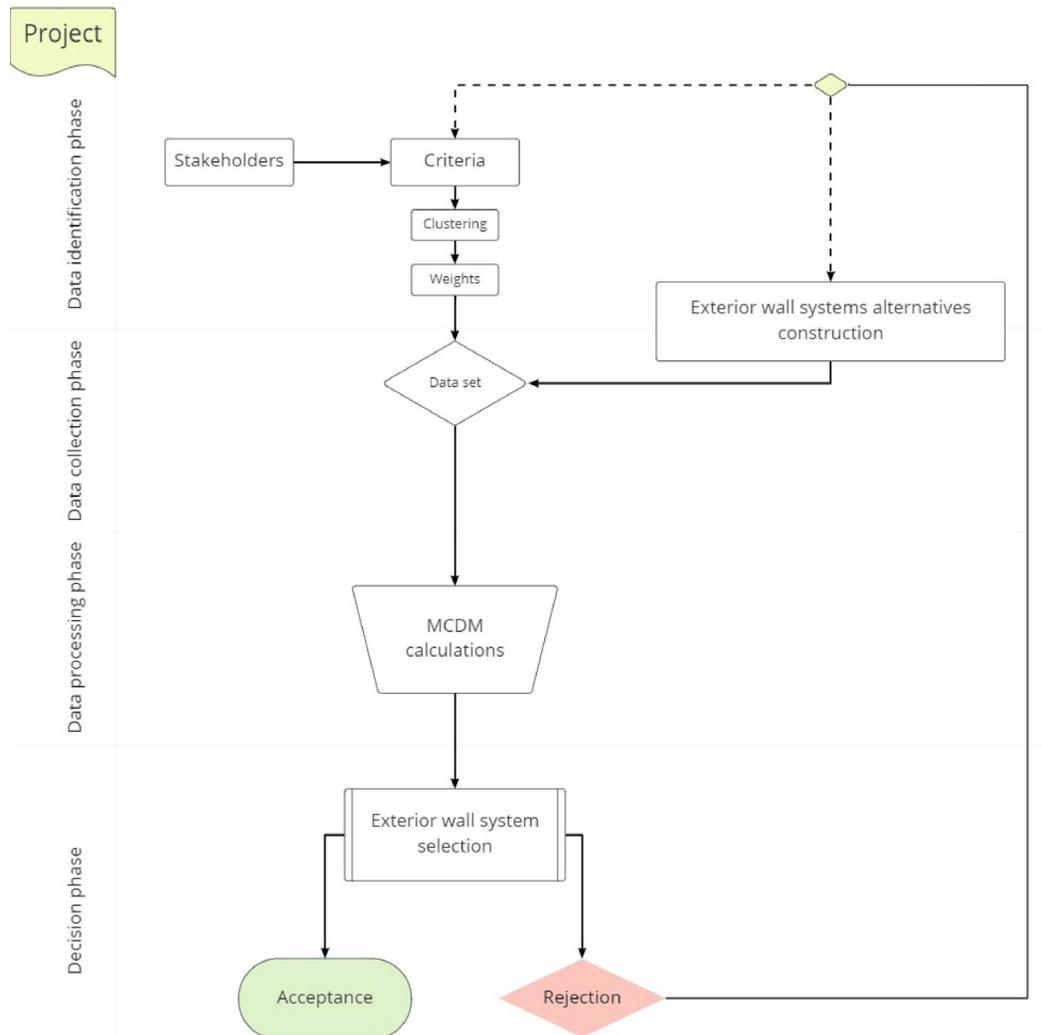

FIG. 2 Research methodology

The research methodology recognized four phases of the research. The phases consisted of Data Identification, Data Collection, Data Processing, and Decision Phase, which dealt with tasks of stakeholder identification; criteria, clustering and weights; exterior wall system alternatives construction; MCDM calculations; and selection of exterior wall system as the objective. The methodology is presented in Figure 2, and phases are explained through the individual tasks in subsections 2.1 – 2.5.

2.1 STAKEHOLDERS

In terms of the paper's research, identification of the stakeholders – decision makers was established as the earliest stage of the research, as a collaborative approach to design and delivery that is supported by key stakeholders – employers, architects, engineers and contractors is a characteristic of idealistic building information modelling (McAdam, 2010).
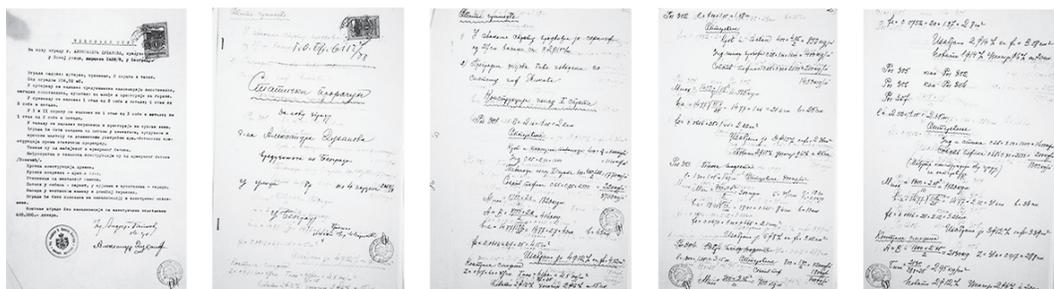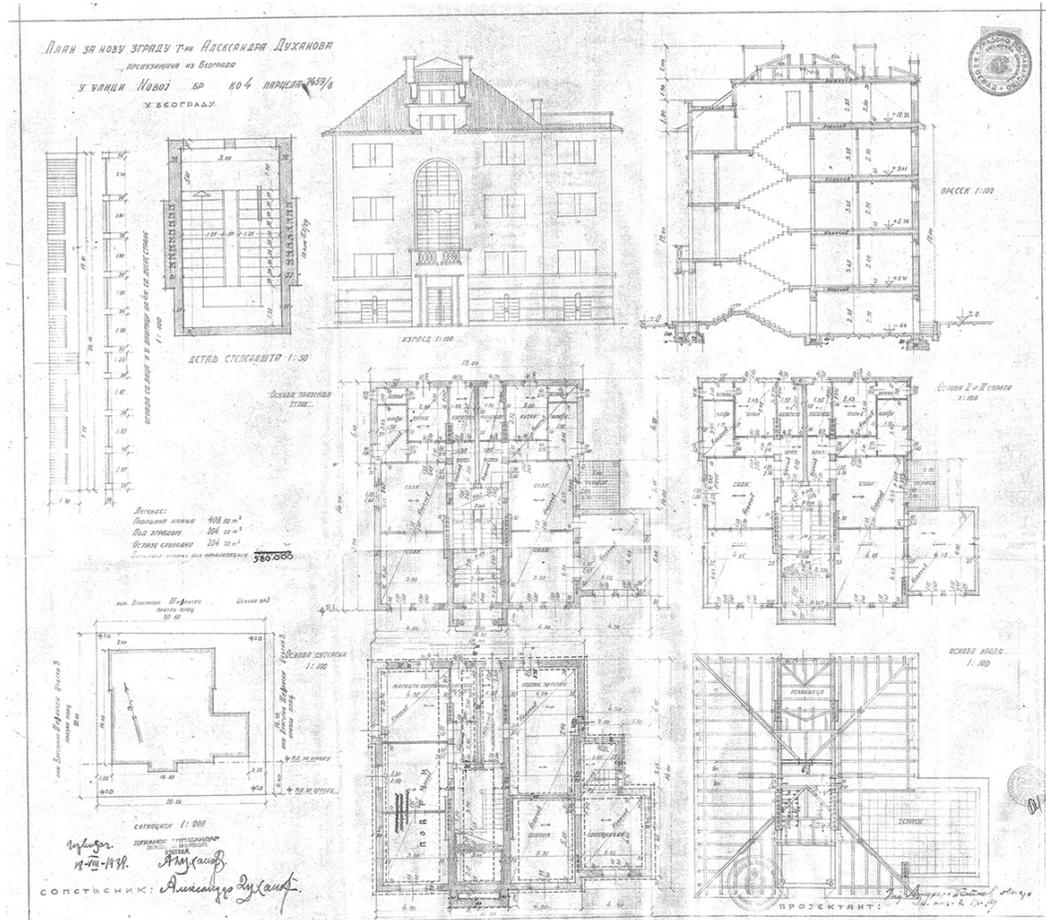

FIG. 3 Archive design and part of static calculations obtained from Historical Archive of Belgrade, Author's presentation

The group of stakeholders included three independent experts: an architect and two civil engineers – building physics and construction expert, who were appointed to the project of additions and

extensions of the case building, as well as the Employer[1]. The contractor (who was also the vendor) was excluded from participating as a stakeholder in this particular case considering his appointment would be made at the stage when exterior wall system has already been selected.

The initial requirements of the Employer were determined in discussions, as well as through the experts' assessment of static impacts and loads by analysing static calculation obtained from the archive design (Figure 3). The initial requirements were prioritising construction deadlines, lightness of the structure (due to a layman's position of the Employer on avoiding the existing structure load), minimizing exploitation costs, and first and foremost: minimizing construction costs.

According to the Employer's request, the Terms of Reference, inter alia, stipulated the desired net usable area of the added section. Therefore, the spatial arrangement had led to the conclusion that it is possible to provide the desired area within the overall horizontal dimensions of the building, only if the façade wall has a maximum layer thickness of 36cm (Figure 4).
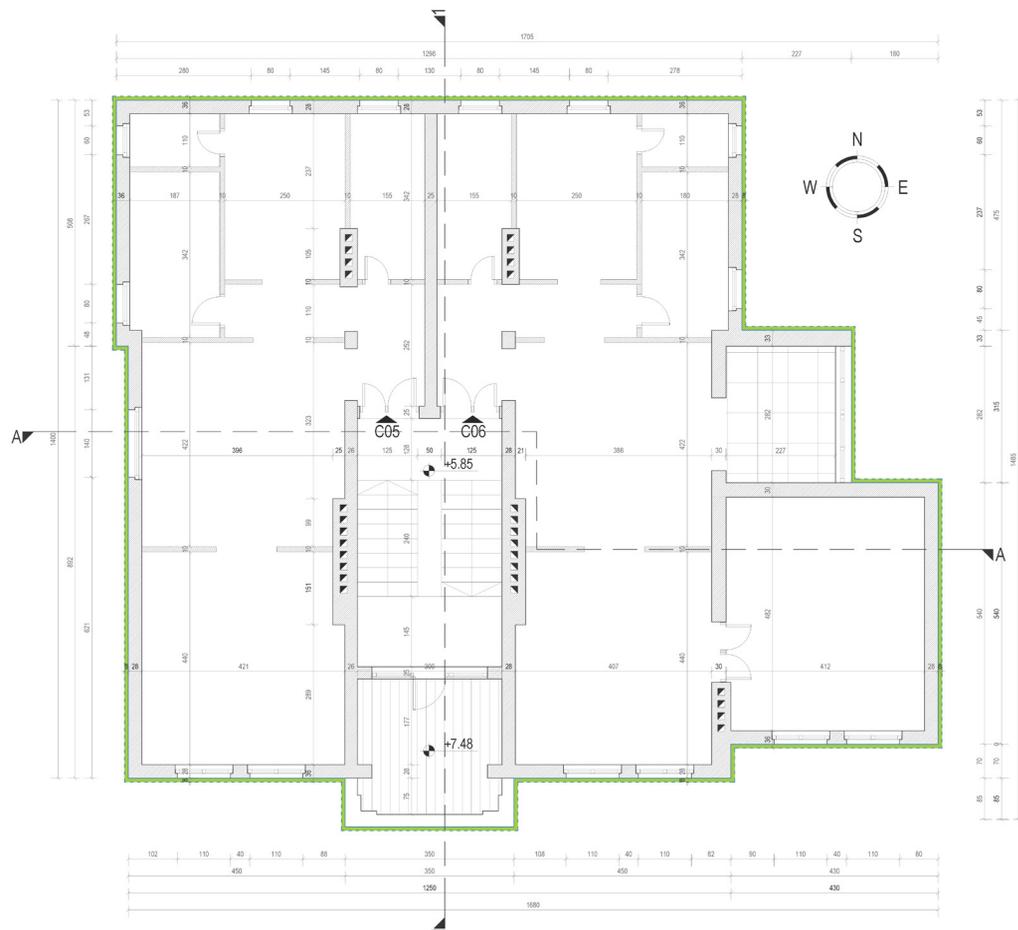

FIG. 4 Typical floor plan of the case study building, Author's drawing based on Archive design and on-site measurements

1   Representative of the group of investors – owners of the apartments in the existing building.

Accordingly, after appointed experts provided a brief explanation of other important factors, the Employer was required to specify the order of priority of stated subjective criteria, while technical criteria were applied based on experts' review of the matter from several different perspectives. Nevertheless, there were also legal and technical frameworks which stipulated possibilities and limitations.

2.2   CRITERIA

As questions expressed as criteria involve decisions in a dynamic environment in which the outcome of a decision is influenced to some extent by the decisions of others, and decisions are frequently dictated by the context in which judgements are made (Weber & Johnson, 2009), the stakeholders were expected to explore and generate "ideas" on their own (Van de Ven & Delbecq, 1971; Harvey & Holmes, 2012; Hugé & Mukherjee, 2018) and to identify criteria using the Nominal Group Technique[2]. Criteria clustering into income and expenditure was conducted and the Delphi based weight determining technique (Hecht, 1977) was used as a tool for determining criteria weights (Figure 5).
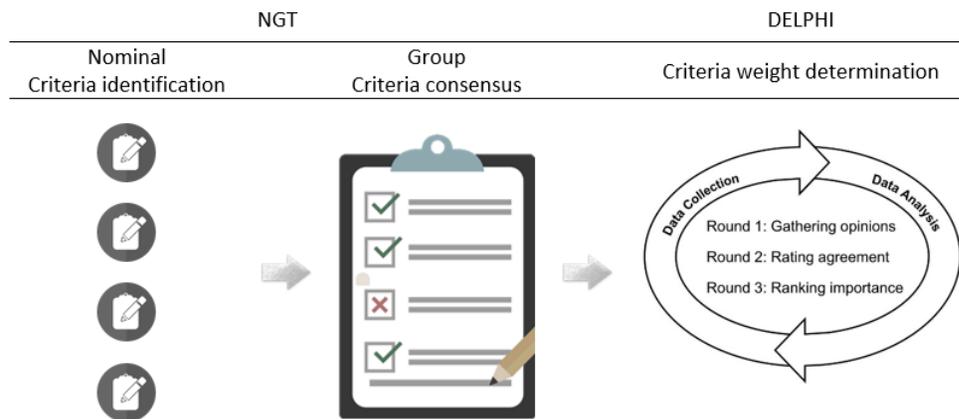

FIG. 5 Criteria identification, clustering and weights phase

In terms of the research presented in this paper, the Employer prepared verbal terms of reference, with the intention of achieving maximum returns with minimum investments. After reviewing the archives (Figure 3), design and static impacts were analysed, the benefits and negative impacts of the location were considered, technical-technological problems, urban conditions (which are not the subject matter in this case) were observed, and the subject matter was reviewed.

By applying NGT, stakeholders proposed two (2) expenditure criteria and eight (8) income criteria, which were in compliance with the commonly-used criteria involved in the decision-making problems in the field (Wen et al., 2021). Detailed descriptions of each criterion will be described hereinafter.

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2   The nominal group technique (NGT) is a structured group-based consensus-building approach. The NGT terminology is derived from the fact that participants are nominally in a group, but are working individually, as NGT is based on a combination of individual and collective reflection. In this case, NGT will be used to identify and clarify problems, as well as to produce appropriate research questions in order to develop solutions and prioritize actions (Hugé & Mukherjee, 2018)

2.2.1   EXPENDITURE CRITERIA

Criterion K1 – Weight – negative impact on the foundation load, was established as the case study of this paper, relating to the extension of and addition to a specified existing building built in 1938. The starting point of discussion was the stability of the facility itself. Considering the facility's and the used materials' life span (Akanbi et al., 2018), as well as the available static calculation (Figure 3) and the currently valid local standards for calculating the load on the existing structure and ground, as well as seismic, wind, and atmospheric phenomena (Bylaw on building constructions, 2020), it was concluded that, in order to avoid additional settling of the structure and its potential collapse, the total mass of the extended part of the building must have as little vertical influence on the existing structure, foundations, and soil as possible (Fajfar, 2017). The presented values of the alternatives will be calculated as actual weight values of the exterior wall system. The values of the alternatives will represent the weight of the exterior wall system, expressed in kg/m^2. (International Organization for Standardization [ISO], 2007b)

Criterion K2 – Total price, i.e. cost of construction – was one of the determining factors (Bari et al., 2012). Pricing is a complex process that requires exact input data obtained through understanding the technologies used to accomplish particular job activities, construction conditions, facility location, and construction standards (Stojanović et al., 2004). Norms applicable in the Serbian region, levelled with average prices on the local market, were used to calculate the labour required to execute and complete the entire, bilaterally processed system. When establishing the price, the purchase price of materials on the local market will be considered, and the values will represent the cost of building a square metre of the exterior wall system. All layers of the system, plastered on the interior side using flexible mortar, whose exterior side is finished with acrylic façade plaster, will be calculated and expressed in EUR/m^2 of the exterior wall system. The total price of system will include the fire protection of core materials that could not obtain a flammability certificate (i.e. wood and steel).

2.2.2   INCOME CRITERIA

Criterion K3 – Reduction in costs of exploitation – will represent the numerical indicator of the exterior wall system maintenance, which will be derived from the aggregate scoring results for the selection of different materials, systems and designs, performance variability, etc. (Chev & De Silva, 2004; Chev et al., 2006). A sustainable façade is defined by the ease of maintenance in terms of design and management, therefore, it is weather resistant and requires minimal life cycle costs, including cleaning, repair and replacement (Yeoh, 1990; Honstede, 1990; Chev et al., 2006). The quantitative indicator will represent aggregated scores of a discrete scale ranging from low (1) to high (5) that will be used to reflect the degree of individual longevity, possibility of intervention on the inner side of the wall, further new or additional installations, possibility of surface cracks, possibility of window replacement or servicing, loss of performance in case of moisture, and behaviour under fire.

Criterion K4[3] – Ease of processing, as an additional acceleration of execution of specialist's trades – has an impact on all subsequent interventions executed on buildings, such as adaptations, change of the intended purpose, laying additional installations. Therefore, it could be referred to as transformability. In addition to convenience and an accelerated installation-laying procedure and finishing of structural elements, workability after installation is exceptionally important (Hendry, 2001). When installing heating, water supply, sewage, and electrical infrastructure, in the case of materials that are not easily workable, if the materials in their structure are not compact, are brittle or excessively hard, the energy efficiency characteristics of the material itself will be affected. The values of the alternatives will present a 1 to 5 scoring scale and will refer to the exterior wall system itself.

Criterion K5 – Local availability of materials – will be presented after careful consideration of the availability of materials in warehouses, the time required to deliver the required quantity of materials, transportation costs (primarily depending on whether material is available on the local / regional / EU market). The transportation of material was taken into consideration as local availability of materials is particularly important, as the ecological and economic advantages could derive from local availability of materials (Rückert et al., 2014). In the case of the addition and extension to an existing building (Figures 1, 3, and 4), which invariably results in unforeseen and additional work, the unavailability of materials due to i.e. country lockdown (Covid-19 era) and border procedures (for transporting imported building materials) would significantly compromise the entire process. A 1 to 5 scoring scale will be established to assess availability.

Criterion K6 – Thermal conductivity coefficient : For many years now, awareness of energy saving, reducing emissions of harmful gases into the atmosphere, using alternative energy sources, all in order to preserve the planet, general health, and the commitment to leave a better living environment for future generations, has been high (Clarke, 2003). Criterion K6 -Thermal conductivity coefficient will be presented through values of the alternatives which refer to the thermal conductivity of the exterior wall system per $1m^2$ of wall surface, expressed in W/m^2K units. The criterion will be determined through the heat transfer coefficient of the applied structural system of the façade wall by applying the calculation methodology stipulated by locally applicable legislation: Serbian Law on planning and construction (2021) and Bylaw on energy efficiency of buildings (2011), based on ISO (2007a), revised version ISO (2017):

$$U = \frac{1}{R_{si} + \sum_n \frac{d_n}{\lambda_n} + R_{se}}$$

Where R_{si} – is heat transfer resistance at entrance, R_{se} – is heat transfer resistance at exit, d_n is $_n$ layer thickness expressed in m (meters) and 1_n – is thermal conductivity coefficient of the $_n$ layer. As the role of layers in selected systems is to prevent outdoor heat release in winter conditions, as well as to reduce the amount of heat that penetrates inside during summer, thermal mass, i.e. the mass of materials used as a part of the façade wall, plays an important part in this process.

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3   The criterion was observed as a completed system with all structural elements and interior finishing elements included.

Criterion K7 – Weight – positive impact on the thermal stability of the building will be presented through the values of the alternatives: actual wall weight expressed in kg/m^2 of the system (ISO, 2007b), and the values will be identical to those given for criterion 1. However, the impact will be as income criterion, as energy savings potential of heavy walls is high (Bellamy & Mackenzie, 2001). The greater the mass of the wall, the more thermally inert the building is.

Criterion K8 – Labour force availability – The need to find skilled labour force (Bari et al., 2012) or provide training for the existing human resources arises in the case of all non-standard procedures. However, even if the training may be simple, it could be lengthy. A 1 to 5 scoring scale will be applied to criterion K8, based on the harmonisation of norms (Mijatović, 2008), building material manufacturer recommendations, and the assessment of experienced human resources available to local companies.

Criterion K9 – Construction speed – was agreed on as an important criterion (Bari et al., 2012) in this case. Criterion will be evaluated by applying the 1 to 5 scoring scale, through the method of execution. Diversification is performed according to the variety of required work – masonry, carpentry, façade, joinery work, ease of handling and workability of elements in terms of construction, transportation, etc. - all based on the harmonisation of norms (Mijatović, 2008) and the recommendations of manufacturers for non-standard building elements.

Criterion K10 – Regulations – certification by domestic institutions- is related to the design phase, where designated institutions (The Ministry of the Interior of the Republic of Serbia) should approve the use of construction materials and where the problem of nostrification of foreign certificates and standards and the need for local standardisation is quite frequent. In addition, the strictness of institutions (The Ministry of the Interior of the Republic of Serbia) regarding fire protection standards for highly flammable materials (Law on fire protection, 2018) slows down the process of issuing building approvals. Therefore, this is considered to be an aggravating factor for walls whose core material is made of wood or steel.

As ten (10) criteria were selected for making a decision regarding the selection of the exterior wall system, they are presented in Table 1.

TABLE 1 Selected criteria

CRITERIA CODE	CRITERIA EXPLANATION	INFLUENCE
K1	Weight - negative impact on the foundation load	Expenditure criterion (↓)
K2	Construction cost	Expenditure criterion (↓)
K3	Reduction in costs of exploitation	Income criterion (↑)
K4	Ease of processing, as an additional acceleration in the execution of specialist's trades	Income criterion (↑)
K5	Local availability of materials	Income criterion (↑)
K6	Thermal conductivity coefficient	Income criterion (↑)
K7	Weight - positive impact on the thermal stability of the building	Income criterion (↑)
K8	Labour force availability	Income criterion (↑)
K9	Construction speed	Income criterion (↑)
K10	Regulations - certification by domestic institutions	Income criterion (↑)

2.2.3 CRITERIA WEIGHT

As elaborated in the description of criteria, there were a certain number of both mutually inclusive and exclusive factors. Therefore, it was decided to weigh criteria based on which materials, i.e. exterior wall system, would be selected. With a small but finite number of stakeholders involved in the reconstruction project, therefore—in the particular case of the extension of a downtown Belgrade building—the Delphi based weight determining technique (Hecht, 1977) as a tool for determining criterions weights, was used to reconcile the individual opinions of the experts and stakeholders, in a group decision.

Both NGT and the modified Delphi technique foresaw the existence of a moderator who communicated with group members independently. After compiling a questionnaire and having individual communications with the team of experts, the focus was placed on those subject matters where disagreement existed among the group members in terms of argumentation or quantitative assessment. More specifically, experts and other stakeholders with the status of decision-makers were asked to express their preferences regarding each criterion individually by giving a percentage score; an example is presented in Figure 6.

FIG. 6 Criteria percentage scoring

The process of answer approximation, decreasing standard deviation, increasing the correlation level – reducing the variation level process, as part of Delphi method (Linstone & Turoff, 2002), was completed after the 3rd round, after which the following weights to the criteria were allocated, as presented in Table 2.

TABLE 2 NGT technique and Delphi method results

CRITERIA CODE	CRITERIA EXPLANATION	WEIGHT	INFLUENCE
K1	Weight - negative impact on the foundation load	0.08	↓
K2	Construction cost	0.22	↓
K3	Reduction in costs of exploitation	0.06	↑
K4	Ease of processing, as an additional acceleration in the execution of specialist's trades	0.08	↑
K5	Local availability of materials	0.10	↑
K6	Thermal conductivity coefficient	0.12	↑
K7	Weight - positive impact on the thermal stability of the building	0.16	↑
K8	Labour force availability	0.06	↑
K9	Construction speed	0.06	↑
K10	Regulations - certification by domestic institutions	0.06	↑

2.3 EXTERIOR WALL SYSTEM ALTERNATIVES

Exterior wall systems are constructed with different physical structures, thermal capacities, and specific gravities, with different installation methods used to achieve the best possible performance of the components of each system, and described in detail.

Within a given total thickness of maximum 36 cm, as presented in Figure 4, exterior wall systems will be formed with core materials belonging to different groups, different physical structures, thermal capacities, and specific gravities, and with different installation methods.

2.4 MCDM CALCULATION

Different MCDM methods, which are employed in the architectural and construction industries, offer generating outputs that can be shown in the form of results and ranking of alternatives. The objective of introducing a MCDM method was to generate a hierarchy (rank) from the set of alternatives.

As a decision-making method, the EDAS method (Keshavarz Ghorabaee et al., 2015) is set for the ranking of exterior wall systems, as one of the methods of multi-criteria decision analysis whose result distribution consistency is confirmed by its high level of Spearman correlation coefficient (Mathew & Sahu, 2018) and which, during segment calculation of positive and negative distance from the mean, and sum weighting, provides insight into the structure of input data and the flows of their transformation up to ranking, inclusive, which may possibly result in the correction of criteria. As some criteria could have a narrow and some could have a broad range of attribute values by criteria, the extension of EDAS method – EDAS+ method (Štilić et al., 2019) is proposed, as the latter eliminates favouring criteria with broader ranges of attribute values. On the other hand, the normalisation implied by EDAS+ makes it somewhat difficult to monitor the fluctuation values of the positive and negative distances from the mean, however, monitoring is still possible.

The method's calculation steps (Štilić et al., 2019; Štilić, 2020) are given hereinafter:

Step 1. Recognizing key criteria, weighting factors for criteria and alternatives in solving the problem of multi-criteria decision making.

Step 2. Forming a decision-making matrix:

$$X = \left[X_{ij} \right]_{nxm} = \begin{bmatrix} x_{11} x_{12} x_{13} \dots x_{1m} \\ x_{21} x_{22} x_{23} \dots x_{2m} \\ x_{31} x_{32} x_{33} \dots x_{3m} \\ \dots \quad \dots \dots \quad \dots \dots \\ x_{n1} x_{n2} x_{n3} \dots x_{nm} \end{bmatrix}.$$

Step 3. Normalizing the decision-making matrix by applying the "Correct mapping":

$$R = \left[R_{ij} \right]_{nxm} = \begin{bmatrix} r_{11} r_{12} r_{13} \quad r_{1m} \\ r_{21} r_{22} r_{23} \quad r_{2m} \\ r_{31} r_{32} r_{33} \quad r_{3m} \\ \\ r_{n1} r_{n2} r_{n3} \quad r_{nm} \end{bmatrix},$$

where $r_{ij} = \dfrac{x_{ij} - x_j^-}{x_j^+ - x_j^-}$, with $i = 1, 2, ..., m$; $j = 1, 2, ..., n$.

Step 4. Determining the average solution for each criterion separately:

$$AV = \left[AV_j \right]_{1xm} = \left[\frac{\sum_{i=1}^{n} x_{i1}}{n} \quad \frac{\sum_{i=1}^{n} x_{i2}}{n} \quad \dots \quad \frac{\sum_{i=1}^{n} x_{im}}{n} \right] = \left[x_1^*, \ x_2^*, ..., x_m^* \right].$$

Step 5. Calculating the positive and negative distance from the mean by taking into account the type of criterion function – income or expenditure:

$$\left[PDA_{ij} \right]_{nxm} : d_{ij}^+ = \begin{cases} \dfrac{max\left(0, \left(x_{ij} - x_j^*\right)\right)}{x_j^*} ; j \in \Omega_{max} \\ \\ \dfrac{max\left(0, \left(x_j^* - x_{ij}\right)\right)}{x_j^*} ; j \in \Omega_{min} \end{cases},$$

$$\left[NDA_{ij} \right]_{nxm} : d_{ij}^- = \begin{cases} \dfrac{max\left(0, \left(x_j^* - x_{ij}\right)\right)}{x_j^*} ; j \in \Omega_{max} \\ \\ \dfrac{max\left(0, \left(x_{ij} - x_j^*\right)\right)}{x_j^*} ; j \in \Omega_{min} \end{cases},$$

where Ω_{max} represents a group of "income" criteria, and Ω_{min} the group of "expenditure" criteria.

Step 6. Calculating the weighted sum matrices:

$$\left[SP_i \right]_{nx1} = \left[PDA_{ij} \right]_{nxm} * \left[W \right]_{mx1} \quad \text{and} \quad \left[SN_i \right]_{nx1} = \left[NDA_{ij} \right]_{nxm} * \left[W \right]_{mx1} \; .$$

Step 7. Normalizing the values of $\left[SP \right]$ and $\left[SN \right]$ for the alternatives:

$$\left[NSP_i \right]_{nx1} = \frac{\left[SP_i \right]_{nx1}}{\left(\max \left[SP_i \right]_{nx1} \right)} = \frac{1}{\left(\max \left[SP_i \right]_{nx1} \right)} * \left[SP_i \right]_{nx1} \text{ and}$$

$$\left[NSN_i \right]_{nx1} = 1 - \frac{\left[SN_i \right]_{nx1}}{\left(\max \left[SP_i \right]_{nx1} \right)} = 1 - \frac{1}{\left(\max \left[SP_i \right]_{nx1} \right)} * \left[SN_i \right]_{nx1} \; .$$

Step 8. Calculating the appraisal score (AS) for the alternatives:

$$AS_i = \frac{1}{2} \left(NSP_i + NSN_i \right) \text{, where: } 0 \leq AS_i \leq 1 \; .$$

Step 9. Ranking the alternatives in order of decreasing of appraisal score (AS) worth. The best option among alternatives is the one with highest AS (Keshavarz Ghorabaee et al., 2017).

2.5   SELECTION BASED ON RESULTS

Comprehension of the ranking results and implementation of the MCDM-derived selection of exterior wall system, as a part of the thermal envelope in the extension building permit and detailed design project, is set as a final phase of the research.

Acceptance of a hierarchy of exterior wall system alternatives should follow, however if the optimal alternative is not adopted in other cases of building extensions, the research phases could be iterated again.

3   EXTERIOR WALL SYSTEM ALTERNATIVES

In order to avoid a naive discussion about generally known materials that could and should be used as core materials for the addition and extension of a multi-floor residential building and to base the selection on an experiential assessment, the employer was presented with exterior wall systems with different physical structures, thermal capacities, specific gravities, and with different installation methods.

In order to form the exterior wall system, core materials belonging to different groups were selected: groups of polystyrene concrete, ceramic/structural clay products, aerated concrete, as well as wooden and steel structures. Fillings, and internal and external linings were arranged so that all systems could have the most similar thermal properties and be mutually competitive. The aim was to achieve the best possible performance of the previously mentioned components of each system, within the given total maximum thickness of 36 cm, which was presented in Figure 4. As an outcome, only contact façades were evaluated.

A more detailed description of selected exterior wall systems is provided hereinafter, and all eight (8) exterior wall systems will be presented through their data in Table 11.
As decided by the authors of this research, the identity of manufacturers of specific materials shall remain confidential, in order to avoid different interpretations of the quality of certain products.
The paper's research focuses on a particular case study and therefore does not offer a general classification of materials at this stage.

3.1 THE EXTERIOR WALL SYSTEM S1
(system belonging to the polystyrene concrete group)

The exterior wall system designated as "S1", presented in Figure 7, is a wall made of polystyrene concrete blocks as core material, with intermittent vertical concrete cores in block cavities.
The exterior wall system S1 could be observed through its vertical cross section: interior plaster -1cm, insulated foam block with periodic concrete cores – 30cm, thermal insulation (XPS) – 5cm, and façade acrylic plaster as the outer layer – 0.5cm.

	d m	ρ kg/m3	λ W/(m×K)	m kg
interior plaster	0,01	1700	0,85	17
polystirol concrete block	0,3	682	0,057	204,52
XPS	0,05	33	0,035	1,65
facade acrilyc plaster	0,005	1850	0,7	9,25
	0,365			**232,42**

U value=   0,160 [W/(m²K)]
*(calculated line transmission losses)

Labels in figure: core mat. / interior plaster 1cm / insulated foam block with periodic concrete cores 30cm / thermal insulation (XPS) 5cm / facade acrilyc plaster 0.5cm / 36,5
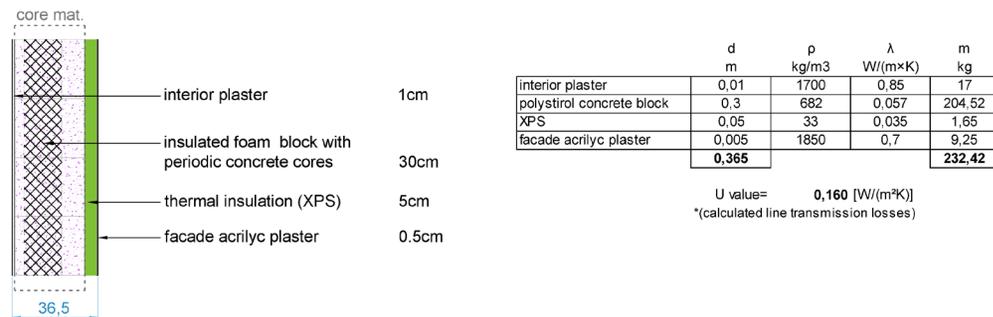
FIG. 7 Exterior wall system S1

This type of wall is characterised by highly rated system solutions in terms of construction, but may have limited availability on the local market depending on the manufacturer and the availability of skilled labour (Table 3). Extremely good thermal characteristics (Ismaiel et al., 2021), but also high price (Figure 7), are some of the distinctive characteristics of this system.

TABLE 3 Exterior wall system S1: Numerical values by criteria

S1	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10
	232.42	101	33	5	2	0.160	232.42	2	4	2

3.2 THE EXTERIOR WALL SYSTEM S2
(system belonging to the polystyrene concrete group)

The exterior wall system designated as "S2", presented in Figure 8, is an exterior wall system whose core material is made of concrete-core polystyrene or extruded polystyrene blocks filled with concrete, as a very good and precise system solution in terms of construction. The exterior wall system S2 could be observed through its vertical cross section: interior plaster -1cm, insulated foam block with constant concrete cores – 30cm, thermal insulation (XPS) – 5cm, and façade acrylic plaster as the outer layer – 0.5cm.


			d m	ρ kg/m3	λ W/(m×K)	m kg
interior plaster			0,01	1700	0,85	17
XPS foam			0,05	33	0,035	1,65
concrete			0,15	2200	2,04	330
XPS foam			0,1	33	0,035	3,3
XPS			0,05	33	0,035	1,65
facade acrilyc plaster			0,005	1850	0,7	9,25
			0,365			362,85

U value= **0,184** [W/(m²K)]
*(calculated line transmission losses)
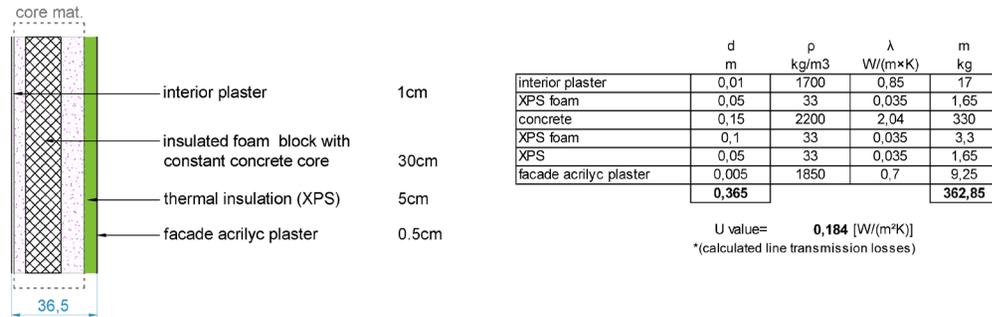
FIG. 8 Exterior wall system S2

This type of wall is characterised by its poor availability on the local market and a significant lack of skilled labour (Table 4). It does not have a wide range of applications, due to smaller design ranges available, however its thermal performances are high (Figure 8). (Ismaiel et al., 2021)

TABLE 4 Exterior wall system S2: Numerical values by criteria

S2	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10
	362.85	109	32	5	1	0.184	362.85	1	4	1

3.3 THE EXTERIOR WALL SYSTEM S3
(system belonging to the ceramic / structural clay products group)

The exterior wall system designated as "S3", presented in Figure 9, is the system whose core material is made of clay. The exterior wall system S3 could be observed through its vertical cross section: interior plaster -1cm, thermally improved ceramic block – 25cm, thermal insulation (XPS) – 10cm and façade acrylic plaster as the outer layer – 0.5cm.

	d m	ρ kg/m3	λ W/(m×K)	m kg
interior plaster	0,01	1700	0,85	17
thermal and acustic inproved	0,25	1200	0,201	300
XPS	0,1	33	0,035	3,3
facade acrilyc plaster	0,005	1850	0,7	9,25
	0,365			**329,55**

U value= **0,256** [W/(m²K)]

FIG. 9 Exterior wall system S3

It has improved thermal properties (Fioretti & Principi, 2014) due to the geometry of the horizontal cross section of the block, lambda value presented in Figure 8, but due to their dimensions the blocks tend to be heavy, and thus, difficult to handle, and processed later. They do offer good availability on local market, there is qualified labour, but like all walls in this group, they do not have sufficiently good thermal characteristics (Caruana et al., 2017), and during the design phase and the actual execution of work, thermal bridges and linear transmission losses are common (Ismaiel et al., 2021).

TABLE 5 Exterior wall system S3: Numerical values by criteria

S3	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10
	329.55	71	22	1	5	0.256	329.55	4	2	5

3.4 THE EXTERIOR WALL SYSTEM S4
(system belonging to the group of ceramic / structural clay products)

The exterior wall system designated as "S4" is a standard hollow ceramic block (ISO, 2007b) presented in Figure 10. The exterior wall system S4 could be observed through its vertical cross section: interior plaster -1cm, standard hollow ceramic block – 25cm, thermal insulation (XPS) – 10cm and façade acrylic plaster as the outer layer – 0.5cm.
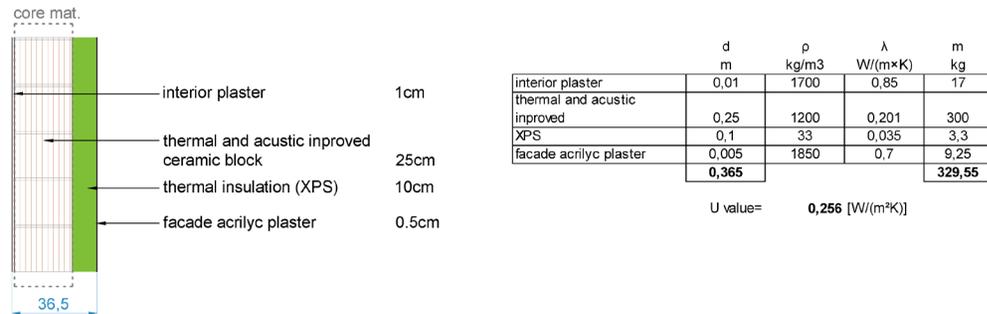

	d m	ρ kg/m3	λ W/(m×K)	m kg
interior plaster	0,01	1700	0,85	17
standard hollow ceramic	0,25	1400	0,61	350
XPS	0,1	33	0,038	3,3
facade acrilyc plaster	0,005	1850	0,7	9,25
	0,365			**379,55**

U value= **0,341** [W/(m²K)]
*(calculated line transmission losses)

FIG. 10 Exterior wall system S4

System S4, with poor thermal properties (Al-Tamimi et al., 2020), is relatively easy to acquire in the Serbian market, local labour force is available, and the cost of construction is very affordable. (Mijatović, 2008) Though as is true of the previous system, there is a risk of thermal bridges, and consequent condensation, moisture, and mould, which results in major problems in terms of its utility.

TABLE 6 Exterior wall system S4: Numerical values by criteria

S4	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10
	379.55	64	21	1	5	0.341	379.55	5	2	5

3.5 THE EXTERIOR WALL SYSTEM S5
(system belonging to the ceramic / structural clay products group)

The exterior wall system designated as "S5" is presented in Figure 11. Standard brick is the most traditional material (Fioretti & Principi, 2014), which is the basis of the system S5. The exterior wall system S5 could be observed through its vertical cross section: interior plaster -1cm, standard brick (25x12.5x6.25cm) – 25cm, thermal insulation (XPS) – 10cm and façade acrylic plaster as the outer layer – 0.5cm.
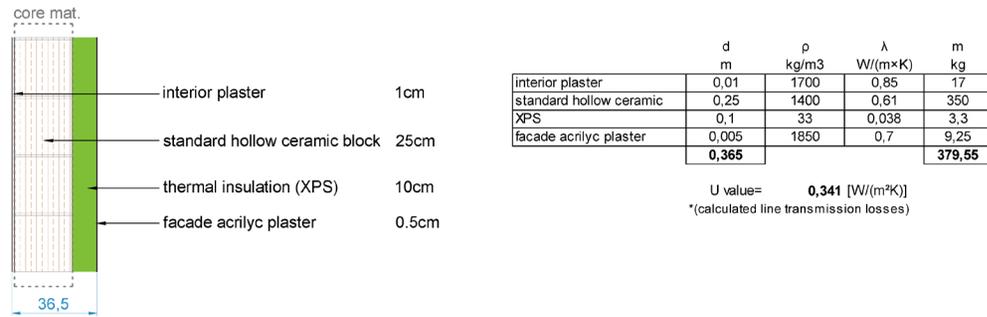

	d	ρ	λ	m
	m	kg/m3	W/(m×K)	kg
interior plaster	0,01	1700	0,85	17
brick	0,25	1800	0,76	450
XPS	0,1	33	0,035	3,3
facade acrilyc plaster	0,005	1850	0,7	9,25
	0,365			**479,55**

U value= **0,326** [W/(m²K)]
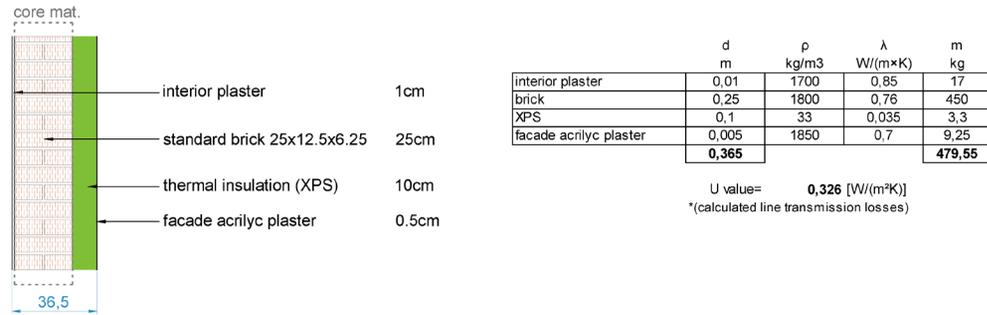*(calculated line transmission losses)

FIG. 11 Exterior wall system S5

This is the system that requires the longest construction time (Mijatović, 2008), and consequently it incurs the highest labour costs (Mijatović, 2008). Construction errors are difficult to correct, despite the fact that elements are easy to process, but subsequent interventions are quite difficult. The great weight of this system ensures the greatest inertia of the building, i.e. temperature stability (Kumar et al., 2017), but it also poses the greatest risk of collapse of the existing structure in the case of poorly installed material. The material is readily available.

TABLE 7 Exterior wall system S5: Numerical values by criteria

S5	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10
	479.55	85	21	2	5	0.326	479.55	5	1	5

3.6 THE EXTERIOR WALL SYSTEM S6
(system belonging to the aerated concrete group)

The exterior wall system designated as "S6", presented in Figure 12, belongs to the aerated concrete group. The exterior wall system S6 could be observed through its vertical cross section: interior plaster -1cm, aerated concrete block – 25cm, thermal insulation (XPS) – 10cm and façade acrylic plaster as the outer layer – 0.5cm.

	d m	ρ kg/m3	λ W/(m×K)	m kg
interior plaster	0,01	1700	0,85	17
aerated concrete block	0,25	460	0,096	115
XPS	0,1	33	0,035	3,3
facade acrilyc plaster	0,005	1850	0,7	9,25
0,365				**144,55**

U value= **0,195** [W/(m²K)]
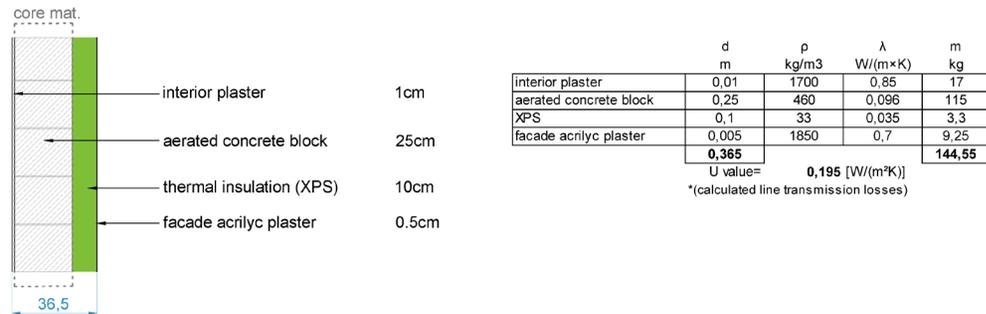*(calculated line transmission losses)

FIG. 12 Exterior wall system S6

With a slightly higher price on the local market than the clay blocks, system S6 is considered to be a desirable exterior wall system due to its plasticity, workability, and relatively good availability on the local market. It has good thermal properties (Ulykbanov et al., 2019), due to its weight aerated concrete block being easy to handle and process, and a labour force is available. The system S6, as observed from practice, is commonly chosen as a (core) building material in Serbia.

TABLE 8 Exterior wall system S6: Numerical values by criteria

S6	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10
	144.55	86	23	4	4	0.195	144.55	4	3	5

3.7 THE EXTERIOR WALL SYSTEM S7
(system belonging to the standard wooden structures' group)

The exterior wall system designated as "S7" is presented in Figure 13. The exterior wall system S7 could be observed through its vertical cross section: double plaster board – 2.5cm, thermal insulation (rockwool) – 8cm, woodboard – 2.5cm, thermal insulation (rockwool) between wooden grill construction – 10cm, woodboard – 2.5cm, thermal insulation (XPS) – 10cm and façade acrylic plaster as the outer layer – 0.5cm. Construction of this system was decided based on good practice and the traditional assembly of wooden structures. (Gojković, 1989)

	d m	ρ kg/m3	λ W/(m×K)	m kg
double plaster board	0,025	900	0,21	22,5
rockwool	0,08	160	0,037	12,8
wood board	0,025	600	0,14	15
rockwool	0,1	80	0,037	8
wood board	0,025	600	0,14	15
XPS	0,1	33	0,035	3,3
facade acrilyc plaster	0,005	1850	0,7	9,25
	0,36			**85,85**

U value= **0,131** [W/(m²K)]
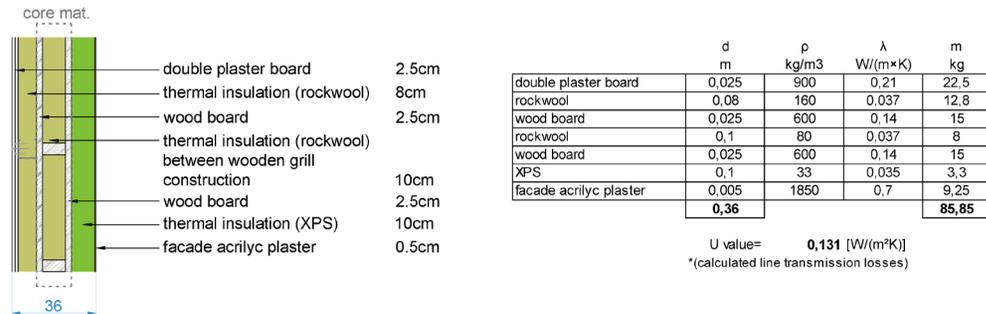*(calculated line transmission losses)

FIG. 13 Exterior wall system S7

The wooden structure of this façade wall has significant advantages, but also limitations. Wood is easily accessible on the local market and it is extremely easy to process. However, a major part of the system consists of thermal insulation materials in the form of filling. Taking into consideration the need to install moisture barriers, multilayer linings, thermal insulation panels, as well as the price thereof, the speed of construction cannot justify the cost (Mijatović, 2008) of such a system. The material is easily accessible, transportable, extremely workable, and easy to handle (Gojković, 1989), but the weight of the wall obtained in this way is low. Therefore, thermal stability represents an unfavourable factor in this system, with summer overheating and winter heat release being poor features of such a wooden wall.

TABLE 9 Exterior wall system S7: Numerical values by criteria

S7	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10
	85.85	92.3	23	3	4	0.131	85.85	3	5	4

3.8 THE EXTERIOR WALL SYSTEM S8
(system belonging to the adapted steel structures' group)

The exterior wall system designated as "S8" is presented in Figure 14. The exterior wall system S8 could be observed through its vertical cross section: double plaster board – 2.5cm, thermal insulation (rockwool) – 8cm, polyurethane sandwich panel – 2.5cm, hollow steel box and steel beam – 8cm, thermal insulation (rockwool) – 8cm, polyurethane sandwich panel – 2.5cm, thermal insulation (XPS) – 8cm and façade acrylic plaster as the outer layer – 0.5cm.

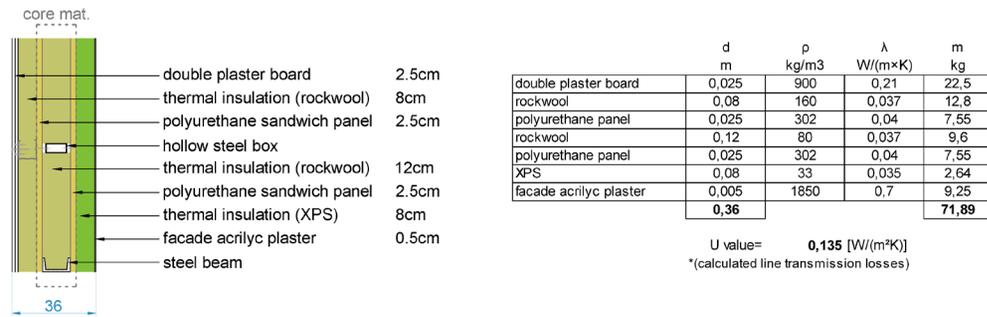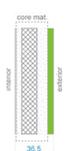|	d m	ρ kg/m3	λ W/(m×K)	m kg
double plaster board	0,025	900	0,21	22,5
rockwool	0,08	160	0,037	12,8
polyurethane panel	0,025	302	0,04	7,55
rockwool	0,12	80	0,037	9,6
polyurethane panel	0,025	302	0,04	7,55
XPS	0,08	33	0,035	2,64
facade acrilyc plaster	0,005	1850	0,7	9,25
0,36				**71,89**

U value= **0,135** [W/(m²K)]
*(calculated line transmission losses)
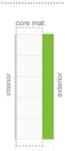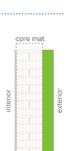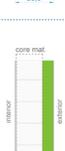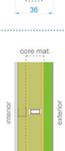
FIG. 14 Exterior wall system S8

Steel structures are frequently utilized to save space because of their density, which results in compact dimensions as a structural element, ensuring space reductions. Steel structures need a highly qualified workforce for the building process, which has a negative impact on price criteria. The dry process during installation certainly allows a faster completion of the building procedure, and accordingly, like the previous exterior wall system (S7), it differs from the other in terms of the interior layer.

TABLE 10 Exterior wall system S8: Numerical values by criteria

S8	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10
	71.89	97	21	2	3	0.135	71.89	3	4	4

For better comparison, exterior wall systems are presented in Table 11. The table is populated with numerical presentation of systems by determined criteria.

TABLE 11 Presenting values of the alternatives by selected criteria

EXTERIOR WALL SYSTEM		K1 ↓ w_1 0,08	K2 ↓ w_2 0,22	K3 ↑ w_3 0,06	K4 ↑ w_4 0,08	K5 ↑ w_5 0,10	K6 ↑ w_6 0,12	K7 ↑ w_7 0,06	K8 ↑ w_8 0,06	K9 ↑ w_9 0,06	K10 ↑ w_{10} 0,06
S1		232.42	101	33	5	2	0.160	232.42	2	4	2
S2		362.85	109	32	5	1	0.184	362.85	1	4	1
S3		329.55	71	22	1	5	0.256	329.55	4	2	5
S4		379.55	64	21	1	5	0.341	379.55	5	2	5
S5		479.55	85	21	2	5	0.326	479.55	5	1	5
S6		144.55	86	23	4	4	0.195	144.55	4	3	5
S7		85.85	92.3	23	3	4	0.131	85.85	3	5	4
S8		71.89	97	21	2	3	0.135	71.89	3	4	4

4 RESULTS AND DISCUSSION

With wide range attribute values observed in Table 11, the extension of EDAS method – EDAS+ method (Štilić et al., 2019) was applied as the method eliminates favouring criteria with broader ranges of attribute values. The application of the method began with the presentation of key criteria and direction of the criterion function, weighting factors for the criteria and alternatives for making choices (Table 11). Under Step 2, formation of a decision-making matrix based on calculated values of different exterior wall systems followed:

$$
X = \left[X_{ij} \right]_{n \times m} = \begin{bmatrix} x_{11} x_{12} x_{13} \dots x_{1m} \\ x_{21} x_{22} x_{23} \dots x_{2m} \\ x_{31} x_{32} x_{33} \dots x_{3m} \\ \dots \quad \dots \dots \quad \dots \dots \\ x_{n1} x_{n2} x_{n3} \dots x_{nm} \end{bmatrix} =
$$

$$
\begin{bmatrix}
232.42 & 101 & 33 & 5 & 2 & 0.160 & 232.42 & 2 & 4 & 2 \\
362.85 & 109 & 32 & 5 & 1 & 0.184 & 362.85 & 1 & 4 & 1 \\
329.55 & 71 & 22 & 1 & 5 & 0.256 & 329.55 & 4 & 2 & 5 \\
379.55 & 64 & 21 & 1 & 5 & 0.341 & 379.55 & 5 & 2 & 5 \\
479.55 & 85 & 21 & 2 & 5 & 0.326 & 479.55 & 5 & 1 & 5 \\
144.55 & 86 & 23 & 4 & 4 & 0.195 & 144.55 & 4 & 3 & 5 \\
85.85 & 92.3 & 23 & 3 & 4 & 0.131 & 85.85 & 3 & 5 & 4 \\
71.89 & 97 & 21 & 2 & 3 & 0.135 & 71.89 & 3 & 4 & 4
\end{bmatrix}
$$

As the Step 3 process continued with normalisation performed by applying a fair mapping method, it resulted in:

$$
R = \left[R_{ij} \right]_{n \times m} = \begin{bmatrix} r_{11} r_{12} r_{13} \circ r_{1m} \\ r_{21} r_{22} r_{23} \circ r_{2m} \\ r_{31} r_{32} r_{33} \circ r_{3m} \\ \circ \circ \circ \circ \circ \\ r_{n1} r_{n2} r_{n3} \circ r_{nm} \end{bmatrix} =
$$

$$
\begin{bmatrix}
0.394 & 0.822 & 1.000 & 1.000 & 0.250 & 0.138 & 0.394 & 0.250 & 0.750 & 0.250 \\
0.714 & 1.000 & 0.917 & 1.000 & 0.000 & 0.252 & 0.714 & 0.000 & 0.750 & 0.000 \\
0.632 & 0.156 & 0.083 & 0.000 & 1.000 & 0.595 & 0.632 & 0.750 & 0.250 & 1.000 \\
0.755 & 0.000 & 0.000 & 0.000 & 1.000 & 1.000 & 0.755 & 1.000 & 0.250 & 1.000 \\
1.000 & 0.467 & 0.000 & 0.250 & 1.000 & 0.929 & 1.000 & 1.000 & 0.000 & 1.000 \\
0.178 & 0.489 & 0.167 & 0.750 & 0.750 & 0.305 & 0.178 & 0.750 & 0.500 & 1.000 \\
0.034 & 0.629 & 0.167 & 0.500 & 0.750 & 0.000 & 0.034 & 0.500 & 1.000 & 0.750 \\
0.000 & 0.733 & 0.000 & 0.250 & 0.500 & 0.019 & 0.000 & 0.500 & 0.750 & 0.750
\end{bmatrix}
$$

Step 4 of the calculation followed:

$$AV = \left[AV_j \right]_{1 \times m} = \left[\frac{\sum_{i=1}^{n} x_{i1}}{n} \quad \frac{\sum_{i=1}^{n} x_{i2}}{n} \ldots \frac{\sum_{i=1}^{n} x_{im}}{n} \right] = \left[x_1^*, \ x_2^*, \ldots, x_m^* \right] =$$

$$= \left[0.463 \quad 0.292 \quad 0.469 \quad 0.656 \quad 0.405 \quad 0.463 \quad 0.537 \quad 0.594 \quad 0.531 \quad 0.719 \right].$$

Steps 5-9, with positive and negative distance from the mean calculations, weighted sum matrices, normalised weighted sums; determined the alternative ranking. Results of the calculation are presented in Table 12.

TABLE 12 Ranking result obtained by applying EDAS+ method

EXTERIOR WALL SYSTEM	SP_i	SN_i	NSP_i	NSN_i	AS_i	RANK
S1	0.352	0.277	0.805	0.389	0.597	1
S2	0.376	0.453	0.858	0.000	0.429	7
S3	0.306	0.240	0.700	0.470	0.585	3
S4	0.438	0.399	1.000	0.120	0.560	5
S5	0.331	0.405	0.757	0.105	0.431	6
S6	0.200	0.128	0.457	0.718	0.588	2
S7	0.269	0.221	0.615	0.512	0.564	4
S8	0.222	0.371	0.507	0.181	0.344	8

As presented in Table 12, calculated AS_i values vary from 0.597 to 0.344, based on which the ranking was obtained. The exterior wall system with the highest AS_i is the best ranked exterior wall system and the results could be observed in the following manner: $S1 < S6 < S3 < S7 < S4 < S5 < S2 < S8$, where the smallest number in the ranking represents the best ranked exterior wall system.

Among eight constructed and presented alternatives of the exterior wall systems, the exterior wall system "S1", a wall made of polystyrene concrete blocks as the core material, with intermittent vertical concrete cores in block cavities, achieved the highest rank by selected and weighted criteria, where the highs of construction possibilities and good thermal characteristics, easy workability and maintainability, counterbalanced the lows of limited availability on the local market, a lack of skilled labour and a high price, among other criteria.

Taking into account the three most highly valued criteria, we could observe that the exterior wall system "S1" (Figure 7) has the most unfavourable values reflected in the price, which is often the key determinant for investors. On the other hand, "S1" values in the other two criteria, thermal mass and thermal conductivity, stay ahead in the competition. By examining the ranking results, the rank of the exterior wall system "S1" could raise the question of production representation, and future prospects of specific core materials on the Serbian market.

In case of selection of the exterior wall system as a part of the thermal envelope for the extension of a multi-family 1938 residential building in Belgrade – Serbia, the Employer accepted the MCDM derived selection, and system "S1" will be used in the project for the extension building permit and detailed design.

$$AV = \left[AV_j \right]_{1 \times m} = \left[\frac{\sum_{i=1}^{n} x_{i1}}{n} \quad \frac{\sum_{i=1}^{n} x_{i2}}{n} \ldots \frac{\sum_{i=1}^{n} x_{im}}{n} \right] = \left[x_1^*, \ x_2^*, \ldots, x_m^* \right] =$$

5 CONCLUSION

Architecture, urban planning, and energy-efficient construction often recognize the need to take into account a wide range of preferences and opinions, both from experts and residents/users of the facilities (Ogrodnik, 2019). In the architectural – construction industry, selection of the optimal materials and exterior wall systems is a complex task (Tian et al., 2018).

Following the methodology of the research, involving experts as stakeholders through NGT and Delphi based method and applying MCDM method (EDAS+) in the process of selection of the *exterior wall system* as a part of the thermal envelope for the extension of a multi-family 1938 residential building in Belgrade – Serbia, resulted in determining measurable and comparable values of the systems and ranking that was presented.

The question of how to make the most appropriate selection of an exterior wall system, when decisions about material selection frequently come down to a choice based on tradition or recommendations based on the experience of the appointed engineers, was answered through the selection of the optimal and adequate exterior wall system whose rank was not reflected in maximising each of the criteria (Moghtadernejad et al., 2020) but through a balance between the various criteria in the set.

The study's research resulted in an exterior wall selection hierarchy that benefited both the employer and the appointed engineers. The numerical indicator ranked the most commonly used (locally) exterior wall system second, after the S1 system; this comprised a wall made of polystyrene concrete blocks with intermittent vertical concrete cores in block cavities, which is not commonly used in practice in Serbia. The Employer's standpoint shifted from recommendations to concise data on which he could make an educated decision as a result of a systematic decision-making process.

The freestanding, multi-family subject building is typical of the Belgrade municipality where it is located. Bearing in mind the typology of the building and urban constraints in GRP by The Institute of Urbanism Belgrade (2016) for the building area of the local self-government unit – the City of Belgrade, study results are applicable to other cases of building extensions. From this perspective, benefits for the (appointed) engineers could be in support of the exterior wall systems' proposal in future projects.

Even though limitations of the rank could represent its singularity, the case of the extension of the particular 1938 Belgrade building and a "real-life" situation of involved stakeholders' subjective opinions, as well as experts' opinions, through the selection of criteria, assigned weights, and proposed exterior wall systems, provided a replicable systematic decision-making process for selecting an exterior wall system that may be utilized in future extension projects of the same multi-family building typology.

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