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The Role of Façade Materials in Blast-Resistant Buildings: An Evaluation Based on Fuzzy Delphi and Fuzzy EDAS

Hamidreza Hasheminasab [1], Sarfaraz Hashemkhani Zolfani [2,*], Mahdi Bitarafan [3], Prasenjit Chatterjee [4] and Alireza Abhaji Ezabadi [5]

1 School of Civil Engineering, College of Engineering, University of Tehran, 16th Azar St., Enghelab Sq., Tehran 1417466191, Iran; Hasheminasab@ut.ac.ir
2 School of Engineering, Catholic University of the North, Larrondo 1281, Coquimbo 1780000, Chile
3 Department of Risk Management, International Institute of Earthquake Engineering and Seismology, Tehran 1953714453, Iran; mehbita@gmail.com
4 Department of Mechanical Engineering, MCKV Institute of Engineering, Howrah 711204, West Bengal 711204, India; prasenjit2007@gmail.com
5 Amirkabir University of Technology (Tehran Polytechnic), Technology Foresight Group, Department of Management, Science and Technology, Tehran 15854413, Iran; abhaji.alireza@gmail.com
* Correspondence: sa.hashemkhani@gmail.com

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Abstract: Blast-resistant buildings are mainly used to protect main instruments, controllers, expensive equipment, and people from explosion waves. Oil and gas industry projects almost always include blast-resistant buildings. For instance, based on a hazard identification (HAZID) and hazard and operability (HAZOP) analysis of a plant, control rooms and substations are sometimes designed to withstand an external free air explosion that generates blast over pressure. In this regard, a building façade is considered to be the first barrier of resistance against explosion waves, and therefore a building façade has an important role in reducing a building's vulnerability and human casualties. In case of a lack of enough resistance, explosion waves enter a building and bring about irreparable damage to the building. Consequently, it seems important to study and evaluate various materials used in a façade against the consequences of an explosion. This study tried to make a comparison between different types of building facades against explosion waves. The materials used in a building play a key role in the vulnerability of a building. In this research, a literature review and the fuzzy Delphi method were applied to find the most critical criteria, and then a fuzzy evaluation based on the distance from the average solution (EDAS) was applied in order to assess various materials used in building facades from the perspective of resiliency. A questionnaire was presented to measure effective indices in order to receive experts' ideas. Finally, by implementing this methodology in a case study, it was concluded that a stone façade performs much better against explosions.

Keywords: Façade materials; explosion; blast-resistant buildings; multiple-criteria decision-making (MCDM); fuzzy Delphi; fuzzy evaluation based on the distance from the average solution (EDAS)

1. Introduction

Blast-resistant buildings are designed for use in hazardous industries, such as oil and gas industry projects where various types of fires (such as pool and jet fires) as well as vapor cloud explosions are common in different hazardous scenarios. These multidisciplinary complicated projects have a clear path to specify hazards and explosions in order to define the necessity of blast-resistant buildings. In this regard, first, different hazards through a hazard and operability

(HAZOP) and hazard identification (HAZID) analysis are identified. Consequently, a safety impact level analysis (SIL) evaluates the probability of safe operation in different risky scenarios. Afterwards, based on a consequence analysis (CA), a project is zoned, and its layout is designed. Finally, if important buildings, such as control rooms, are located in one of the hazardous areas, the building has to be designed to resist an explosion wave.

Identifying probable and possible dangers means a critical role in preparing to confront and resist the negative effects of radical attacks in urban zones and regions. The main aim of pathology is to identify facilities, immunize the answers of buildings to radical attacks, and resist the effects of explosions [1]. On the one hand, the resistance of a building to an explosion wave depends on the shape and the form of the building and the roof, the number of entries and casements, and the power and genus of the materials used. On the other hand, a building façade is considered to be the first barrier protecting against waves of a proximate explosion. Thus, it seems important to study and evaluate various materials used in a façade against the consequences of an explosion. In Iran, an outer façade is usually built after constructing the outer wall, which consists of some materials such as decorative brick, cement, and stone.

This research compared different types of building facades against explosion waves. The materials used in a building play an important role in a building's vulnerability. Considering the influence and role of building materials in the effects of an explosion, buildings can be classified into three different categories, according to studies of and experience from previous wars and recent wars [2]:

- Buildings with damage-aggravating materials: A glass façade can be considered to be an example of this category. Basically, glass facades severely increase people's vulnerability to the environment. The surface under falling glass pieces will extend proportionally to incremental height. Thus, a lot of fatal glass pieces will be thrown outside just by the effects of the sonic barrier being broken;
- Buildings with vulnerable materials: Some materials or a combination thereof are not resistant enough against waves and quivers, and they will cause serious damage at the time of an explosion;
- Buildings with fewer vulnerable materials: Some buildings whose façades are composed of rigid-like materials, such as concrete, or a combination of materials, such as fibrous concrete, can be put into this category. These buildings can be more resistant to explosions and will be less vulnerable. Thus, due to the mentioned cases, the main goal of this research was the absence of indices for assessing and selecting the best kinds of materials to use in the façades of buildings in Iran. In the field of buildings resistant to explosion, a lot of research has been done. Some of it is mentioned now.

Gebbeken & Döge [3] studied the structure geometry of preventing blast waves from getting to buildings. The results fundamentally concluded that in geometric shapes, maximum pressures and maximum impulses depend on the distance from the explosion location, the confliction angle of explosion waves, and the resistance to the progress of waves of structural shapes. The shape of structural ingredients or building ingredients is certainly able to decrease explosion loads.

Barakat & Hetherington [4] accomplished similar research. Their study was of blast effects on different forms of structures, such as cubic, cylinder, half-cubic, and prismatic forms, and they concluded that in addition to the structural components of a building, architectural forms can also have a great effect on reducing explosion effects on buildings. Mojtahed Pour [5] can be mentioned as another example. In this study, the effects of structure shape on stress distribution from explosion loading was examined: In addition, the research was more on structural aspects of the issue, as in some parts he focused on the effect of indicatives in structures.

Luccioni et al. [6] can also be pointed to as a related and important study in this area. The aim of this study was a failure analysis of buildings with concrete structures under an explosion load. They modeled a three-dimensional model from a concrete building using ANSYS Autodyn software and concluded that the failure mechanism started from the lower columns of the building, and the building was destroyed. Buildings resistant to explosion have developed through so many studies

[7–13]. These studies have focused on the impact of architectural elements on the vulnerability of structures to earthquake hazards.

The federal agency Crisis Management of America accomplished some research on buildings resistant to explosion. For instance, the research of the Federal Emergency Management Agency (FEMA) number 426 [14] can be mentioned, which presented some finite regulations for designing building façades and some factors, such as casements and the genus of mentioned materials.

As mentioned in the history of the research, many studies in the field of buildings resistant to explosion have been done so far. In this study, some types of building facades and related materials that are commonly used for resisting explosions were considered. Consequently, the characteristics of each façade material were investigated. Then, the research methodology used was a pairwise assessment to evaluate the efficiency of different facades based on the presented indices (criteria). Finally, as the conclusion, the most appropriate kind of façade is presented as the first resistance barrier against an explosion. In doing such a study, the best kind of facade is specified in order to reduce damage from an explosion to an acceptable level of damage through observing the obtained results from this research, which should be applied to buildings built in Iran in the future.

2. Types of Materials in Building Facades

The types of most widely used facades in Iran are as follows.

2.1. Brick Façade (A_1)

Brick, which is usually performed on the outer walls of buildings, is one of the oldest materials in façades in Iran. The color and quality of the mentioned bricks differ from other types of bricks. The most common types of façade bricks are Cossack bricks, Bahmani bricks, 3-cm bricks, and fireproof bricks. The advantages and disadvantages of bricks are discussed here.

Due to the rigidity of this type of façade, the ability to transfer energy from an explosion to the outer wall of a building is high, and consequently this does not have enough of an effect on reducing an explosion effect.

Due to the heavy weight of the brick and the possibility of detachment of the crustal from the outer wall, such a façade is not suitable enough for debris removal.

Due to integration and simultaneous implementation, some large surfaces have less of a reconstruction ability.

Due to the high thermal capacity of the brick in this façade, it has an appropriate capability against fire.

2.2. Stone Façade (A_2)

Due to the rigidity of this type of façade, the ability to transfer energy from an explosion to the outer wall of a building is high, and consequently this does not have enough of an effect on reducing the explosion effect on a building.

Due to the heavy weight of the building stones and the possibility of detachment of the crustal from the outer wall, such a façade is not suitable enough for debris removal.

Due to integration and simultaneous implementation, some large surfaces have less of a reconstruction ability.

Due to the high thermal capacity of this type of façade, it has an appropriate capability against fire.

2.3. Coatings Cement Façade (A_3)

Due to the low thickness of the materials used in this type of facade, the ability to transfer energy from an explosion to the outer wall of a building is high, and consequently this does not have enough of an effect on reducing explosion effects.

Due to its low weight and the adherence of a concrete façade to an outer wall, in such a façade there is not much debris.

Due to the type of implementation, it has a high reconstruction ability.

Due to the low thickness of the materials in this façade, it has little effect against fire.

2.4. Composite Façade (A_4)

Due to the lack of rigidity in this type of façade, the ability to transfer energy from an explosion to the outer wall of a building is lower, and consequently this has a high effect on reducing the explosion effect on a building.

Due to its low weight and a proper connection to the outer wall, such a façade seems to be suitable enough for debris removal.

Due to a lack of integration and block implementation, it has a high reconstruction ability.

Due to the low thermal capacity of this type of façade, it has an appropriate capability against fire.

2.5. Curtain Wall (A_5)

Due to the lack of rigidity in this type of façade, all waves and quivers from an explosion enter a building easily.

Debris from the shattering of glass causes injuries to people and damage to equipment.

Due to the low thickness of glass and its material characteristics, it is not capable enough against fire.

Due to glass having a lack of resistance to explosion, it will be completely destroyed and will need to be replaced completely.

3. Methodology

In this study, first, the materials used in building façades in Iran were identified through library resources in order to evaluate the materials used in buildings to protect building façades from the effects of an explosion. Second, all of the indicators on the long proposed list were extracted by interviewing experts in the fields of civil engineering and architecture (Table 1 for the case study) to assess building façades against the effects of an explosion. Next, a Delphi technique in combination with fuzzy set theory (to cope with uncertainty) was used to evaluate the identified criteria list to represent the most important criteria list to be used in an assessment process. Then, a questionnaire was presented to a panel of experts to obtain their ideas in order to measure effective indices. For this purpose, fuzzy Delphi applied to select and examine criteria. Eventually, priorities and the final weight of indices were determined through fuzzy EDAS. The procedure and process of the research is shown in Figure 1.

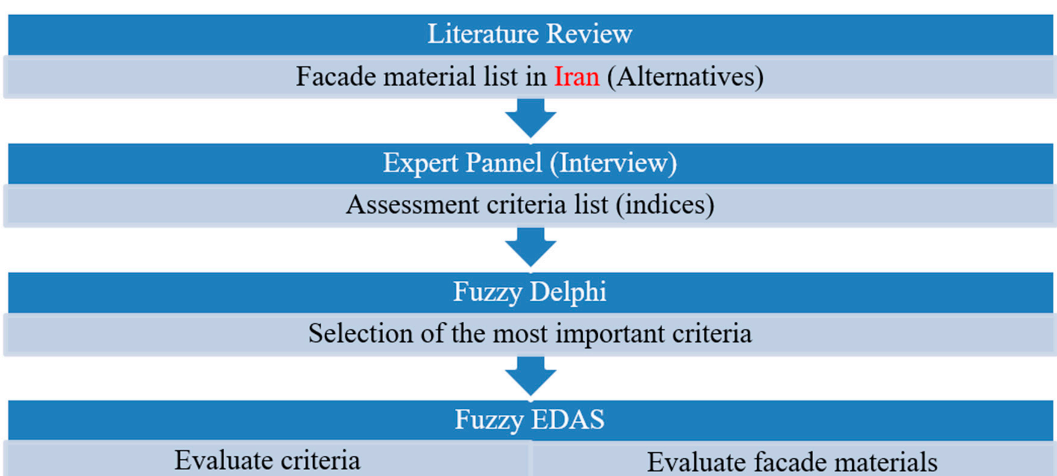

Figure 1. The process of the research.

This approach tries to make results more robust in comparison to common approaches in the Multiple Attribute Decision Making (MADM) field. This study tried to apply fuzzy logic, a literature review, and a Delphi method to suggest the best criteria for evaluating proposed alternatives. Fuzzy EDAS was applied to consider all alternatives more accurately (as much as possible) based on expert evaluations.

3.1. Fuzzy Delphi

Different fuzzy Delphi techniques have been presented in the multiple-criteria decision-making (MCDM) literature. However, this study was developed based on a classic form of the method [15]. The proposed technique in this study was a combination of gray numbers, fuzzy set theory, and a Delphi technique, as follows.

Step 1 (expert panel): Experts were asked to provide an interval value (gray number) as a representation of the relative importance of the intended criteria. Here, $[q_k^{(i)}.r_k^{(i)}]^{(p)}$ denotes the *i*th respondent in the *k*th iteration for the *p*th alternative.

Step 2 (fuzzification): The interval values were turned into a fuzzy membership function based on the frequency and overlap of the intervals developed by the panel of experts. Thus, based on the experts' responses, the universe was divided into some intervals to calculate the frequencies through the following methodology:

$$y_s^{(p)} = \sum_{i=1}^{I} \delta_s^{(i.p)}, \quad (1)$$

where I denotes the number of experts participating in the research, and $y_s^{(p)}$ denotes the primary membership function for the fuzzy number related to the *p*th alternative,

$$\delta_s^{(i.p)} = \begin{cases} 1 & if\ x_s \in [q_k^{(i)}.r_k^{(i)}]^{(p)} \\ 0 & Otherwise \end{cases}. \quad (2)$$

Step 3 (normalization): The fuzzy number measured for every criterion was divided by the highest value so that the membership function was defined between 0 and 1:

$$y_*^{(p)} = \max_{s=1.....S}\left\{y_s^{(p)}\right\}, \quad (3)$$

$$Y^{(p)}(x_s) = \frac{y_s^{(p)}}{y_*^{(p)}}. \quad (4)$$

Step 4 (defuzzification): The center of gravity (COG) was the proposed methodology used to defuzzify the proposed fuzzy number. Finally, the average value for each criterion was measured:

$$\overline{COG^{(p)}} = \frac{\int Y^{(p)}(x_s)\times x_s\times d(x_s)}{\int Y^{(p)}(x_s)\times d(x_s)}. \quad (5)$$

Step 5 (consensus evaluation): If the linear absolute distance of the calculated average value ($\overline{COG^{(p)}}$) with all of the respondents' defuzzified values (the COG) was less than 0.7, the answer converged and the process for this criteria was stopped.

3.2. Fuzzy Evaluation Based on the Distance from the Average Solution (Fuzzy EDAS)

EDAS is an effective MCDM methodology that was developed in 2015 based on measuring the deviation from the average solution. The efficiency of this MCDM methodology has been evaluated in comparison to prior valid methodologies, such as Vlse Kriterijumska Optimizacija Kompromisno Resenje (VIKOR), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Simple Additive Weighting (SAW), and COmplex Proportional Assessment (COPRAS), with consistent results [16]. As ambiguity is an important condition in most problems, a combination of fuzzy set theory and EDAS was developed one year later [17].

Recently, fuzzy EDAS has been developed in new studies, and some new ones are mentioned here (as follows):

- In supplier selection [17];
- In solid waste disposal site selection [18];
- For subcontractor evaluation [19];
- For supplier evaluation and order allocation with environmental considerations [20];
- For the evaluation of construction equipment with sustainability considerations [21];
- In hydrogen mobility roll-up site selection [22];
- For evaluating suppliers [23].

In this study, fuzzy EDAS methodology and its calculation procedure were mainly based on previous studies [17], as follows.

An assessment methodology was proposed through the following five steps.

Step 1 (determining the average distance): We assumed *n* alternatives were defined as a screened building façade and *m* criteria were considered in the assessment process. In addition, the number of respondents was set as *k*. Thus, the average distant matrix was calculated as follows:

$$\tilde{x}_{ij} = \frac{1}{k}\left(\bigoplus_{p=1}^{k} \tilde{x}_{ij}^{p}\right) \Rightarrow X = \left[\tilde{x}_{ij}\right]_{n\times m}, \quad (6)$$

where $\tilde{x}_{ij}^{p}$ denotes the *p*th respondent opinion about alternative *i* with respect to the *j*th criterion.

Step 2 (calculating criteria weight): The criteria average weight based on the respondents' opinions was calculated as follows:

$$\widetilde{w}_{j} = \frac{1}{k}\left(\bigoplus_{p=1}^{k} \widetilde{w}_{j}^{p}\right) \Rightarrow W = \left[\widetilde{w}_{j}\right]_{1\times m}, \quad (7)$$

where $\widetilde{w}_{j}^{p}$ denotes the weight of the *p*th respondent on the *j*th criteria weight.

Step 3 (negative and positive distances from the average): Average responses with regard to every criterion were calculated as follows:

$$\widetilde{av}_{j} = \frac{1}{n}\left(\bigoplus_{i=1}^{n} \tilde{x}_{ij}\right) \Rightarrow AV = \left[\widetilde{av}_{j}\right]_{1\times m}. \quad (8)$$

Then, the positive distance from the average (pda), as well as the negative (nda), were calculated as follows:

$$\widetilde{pda}_{ij} = \frac{\Psi\left(\tilde{x}_{ij}\ominus\widetilde{av}_{j}\right)}{\kappa\left(\widetilde{av}_{j}\right)} \Rightarrow PDA = \left[\widetilde{pda}_{ij}\right]_{n\times m}, \quad (9)$$

$$\widetilde{nda}_{ij} = \frac{\Psi\left(\widetilde{av}_{j}\ominus\tilde{x}_{ij}\right)}{\kappa\left(\widetilde{av}_{j}\right)} \Rightarrow NDA = \left[\widetilde{nda}_{ij}\right]_{n\times m}, \quad (10)$$

where $\Psi(\tilde{x}) = \max(\tilde{x}, 0)$, and $\kappa(\tilde{x})$ is the defuzzification function.

Consequently, the calculated distances from the average were weighted as follows:

$$\widetilde{sp}_{i} = \bigoplus_{j=1}^{m} \left(\widetilde{w}_{j}\otimes\widetilde{pda}_{ij}\right), \quad (11)$$

$$\widetilde{sn}_{i} = \bigoplus_{j=1}^{m} \left(\widetilde{w}_{j}\otimes\widetilde{nda}_{ij}\right). \quad (12)$$

Step 4 (calculating the normal value): In order to calculate the normal value and remove the units, all of the values had to be divided by a maximum value, as follows:

$$\widetilde{nsp}_i = \frac{\widetilde{sp}_i}{\max_i \kappa(\widetilde{sp}_i)}, \tag{13}$$

$$\widetilde{nsn}_i = 1 - \frac{\widetilde{sn}_i}{\max_i \kappa(\widetilde{sn}_i)}. \tag{14}$$

Step 5 (calculating the alternatives' score and ranking): Based on the proposed methodology, assessment scores were calculated as follows:

$$\widetilde{as}_i = \frac{1}{2}(\widetilde{nsp}_i \oplus \widetilde{nsn}_i). \tag{15}$$

4. Case Study

4.1. Data Gathering

First, top managers of an organization with proven experience in crisis management and a group of experts in civil engineering, architecture, and the economy participated in a conference meeting to make decisions in this regard, and the team determined four important criteria for reconstructing damaged areas during a natural crisis. Information about the experts is shown in Table 1.

Table 1. Background information of experts.

Field	Education	No.
Civil Engineering	Bachelor's	3
	Master's	7
	PhD	2
Architecture	Bachelor's	0
	Master's	6
	PhD	4
Top managers	Bachelor's	0
	Master's	2
	PhD	1

4.2. Determining Effective Indices for Selection

Effective indices were determined upon assessment of the various types of materials used in building façades in Iran for their resistance to the effects of explosion by gathering experts' ideas as well as reviewing the literature for those criteria which used in resistant façade evaluation. Decision-making indices, which consisted of a set of economic and executive characteristics, are shown in Table 2.

Table 2. Assessment indices of façade materials in blast-resistant buildings.

Symbol	Criteria
C_1	Reducing explosion effects capability
C_2	Debris removal capability
C_3	Resistance to fire capability
C_4	Reconstruction capability
C_5	Implementation costs
C_6	Skilled technician availability
C_7	Access to material supply
C_8	Maintenance costs
C_9	Environmental footprint
C_{10}	Reducing energy loss

4.3. Criteria Screening

In order to enhance the efficiency of the assessment, the criteria were screened (as seen in this section) by using fuzzy Delphi. Experts were asked to specify the importance of the criteria according to the specified scale. The following criterion is presented as an example of the calculation procedure.

Scales for expert judgment:

1. Totally irrelevant (1–3);
2. Irrelevant (2–4);
3. Relatively relevant (4–6);
4. Relevant (6–8);
5. Totally relevant (7–9).

The mentioned scale was a guide to speed up the consensus efficiency and narrow down the range of gray numbers assigned to a particular criterion. Hence, experts at first chose a specific overall range and consequently defined their exact proposed gray numbers. This assisted experts by categorizing the criterion, leading to a more accurate decision.

Table 3. Experts' opinions on a selected criterion.

	Criteria	Primary Category	Final Decision
C_5	Implementation costs	Relevant	12 experts: 7–8 11 experts: 6–8 2 experts: 6–7

The following Table 4 represents the fuzzy Delphi technique, based on experts' opinions as it can be seen in Table 3, which was developed based on classic methodology [15] and the experts' opinions.

Table 4. Fuzzification and defuzzification of the experts' opinions. COG: Center of gravity.

Expert (*i*)	$\delta_9^{(i.5)}$	$\delta_8^{(i.5)}$	$\delta_7^{(i.5)}$	$\delta_6^{(i.5)}$	$\delta_5^{(i.5)}$	$\delta_4^{(i.5)}$	$\delta_3^{(i.5)}$	$\delta_2^{(i.5)}$	$\delta_1^{(i.5)}$
1	0	1	1	0	0	0	0	0	0
2	0	1	1	0	0	0	0	0	0
3	0	1	1	0	0	0	0	0	0
4	0	1	1	0	0	0	0	0	0
5	0	1	1	0	0	0	0	0	0
6	0	1	1	0	0	0	0	0	0
7	0	1	1	0	0	0	0	0	0
8	0	1	1	0	0	0	0	0	0
9	0	1	1	0	0	0	0	0	0
10	0	1	1	0	0	0	0	0	0
11	0	1	1	0	0	0	0	0	0
12	0	1	1	0	0	0	0	0	0
13	0	1	1	1	0	0	0	0	0
14	0	1	1	1	0	0	0	0	0
15	0	1	1	1	0	0	0	0	0
16	0	1	1	1	0	0	0	0	0
17	0	1	1	1	0	0	0	0	0
18	0	1	1	1	0	0	0	0	0
19	0	1	1	1	0	0	0	0	0
20	0	1	1	1	0	0	0	0	0
21	0	1	1	1	0	0	0	0	0
22	0	1	1	1	0	0	0	0	0
23	0	1	1	1	0	0	0	0	0
24	0	0	1	1	0	0	0	0	0
25	0	0	1	1	0	0	0	0	0
	$y_9^{(5)}$	$y_8^{(5)}$	$y_7^{(5)}$	$y_6^{(5)}$	$y_5^{(5)}$	$y_4^{(5)}$	$y_3^{(5)}$	$y_2^{(5)}$	$y_1^{(5)}$
	0	23	25	13	0	0	0	0	0
	$Y^{(5)}(x_9)$	$Y^{(5)}(x_8)$	$Y^{(5)}(x_7)$	$Y^{(5)}(x_6)$	$Y^{(5)}(x_5)$	$Y^{(5)}(x_4)$	$Y^{(5)}(x_3)$	$Y^{(5)}(x_2)$	$Y^{(5)}(x_1)$
	0	0.92	1	0.52	0	0	0	0	0
					$\overline{COG^{(5)}}$				
					7.16				

Based on the calculated average center of gravity for the proposed criteria, the following Table 5 controlled the consensus status.

Table 5. Checking consensus achievement.

Expert (i)	$COG^{(i.30)}$	$ABS(COG^{(i.30)} - \overline{COG^{(30)}})$
1	7.5	0.34
2	7.5	0.34
3	7.5	0.34
4	7.5	0.34
5	7.5	0.34
6	7.5	0.34
7	7.5	0.34
8	7.5	0.34
9	7.5	0.34
10	7.5	0.34
11	7.5	0.34
12	7.5	0.34
13	7	0.16
14	7	0.16
15	7	0.16
16	7	0.16
17	7	0.16
18	7	0.16
19	7	0.16
20	7	0.16
21	7	0.16
22	7	0.16
23	7	0.16
24	6.5	0.66
25	6.5	0.66

As presented in the table, these criteria converged in the first round. In this regard, this methodology applied to all of the criteria, and consequently the results are presented as follows (Table 6).

Table 6. Final criteria ranking for screening.

Symbol	Criteria	$\overline{COG}$
C_1	Reducing explosion effect capability	8.62
C_2	Debris removal capability	3.47
C_3	Resistance to fire capability	6.12
C_4	Reconstruction capability	4.66
C_5	Implementation costs	7.16
C_6	Skilled technician availability	1.96
C_7	Access to material supply	1.45
C_8	Maintenance costs	1.88
C_9	Environmental footprint	1.12
C_{10}	Reducing energy loss	1.34

According to the specified scale, an irrelevant criterion with an average center of gravity of less than 2 was eliminated for the rest of the process. The remaining criteria after the screening phase are briefly defined as follows.

4.3.1. Reducing Explosion Effect Capability (C_1)

The goal of this index was to avoid penetration of the wave and quivers into the building arising due to an explosion. If waves and quivers enter any building, existing people and facilities inside of the space face unrecoverable damage. In other words, the more resistant the materials used in a building façade are to explosion, the less the penetration of waves and quivers is, and a building faces less damage.

4.3.2. Debris Removal Capability (C_2)

Another effective index on selecting the genus of the building outer wall material is the debris removal capability of such materials. Such a capability is important from two aspects. First of all, in the case of falling debris, a higher weight (of materials) brings more damage to people and facilities under the debris. In other words, lighter materials facilitate debris removal, with reduced vulnerability. Second, in the case of some materials breaking, their pieces cause injuries to people inside a building.

4.3.3. Resistance to Fire Capability (C_3)

At the time of explosion, it is possible that buildings around the explosion will fall into a fire. In the case of the outer wall material being resistant to fire, fire penetration into other inner parts of the building will be reduced, and people inside the building will face less damage.

4.3.4. Reconstruction Capability (C_4)

After an explosion and at the end of a relief process, if possible, the building should return to its previous condition, as it was before the explosion. Thus, using materials with a high reconstruction capability is very crucial, as this can return building action to a normal state in a shorter period of time.

4.3.5. Implementation Costs (C_5)

This means all related costs of each alternative. These costs can be diverse and alternatives to others and can be practical or material costs.

4.4. Fuzzy EDAS

The results of calculations carried out according to the proposed methodology are summarized in Tables 7–11. A decision-making matrix (Table 7) (the average distance) was calculated based on the average of experts' opinions about the topic.

Table 7. Average distance.

Alternatives		Criteria				
		C_1	C_2	C_3	C_4	C_5
Brick facade	A1	3.5, 4.4, 4.9	1.2,1.6,1.9	8.4, 8.9, 9	1, 1, 1.2	2.6, 3.1, 3.8
Stone facade	A2	8.1, 8.6, 9	1.6, 2, 2.5	6.8, 7.2, 7.8	1.4, 2.1, 2.6	1.6, 2, 2.7
Coatings cement facade	A3	1.8, 2.6, 3.2	8.4, 8.6, 9	4.2, 4.5, 5.7	8.8, 9, 9	8.7, 9, 9
Composite facade	A4	1.2, 1.6, 2.6	4.1, 4.7, 5.1	1, 1.4, 2.1	4.3, 4.7, 5.3	1, 1, 1.3
Curtain wall	A5	1, 1, 1.2	1, 1, 1.5	1, 1, 1.4	1.1, 1.4, 1.9	1, 1.6, 2.4

Table 8. Criteria weight.

		Criteria				
		C_1	C_2	C_3	C_4	C_5
Average criteria weight	$\widetilde{w}_j$	8.6, 9, 9	4.2, 4.7, 5.8	1, 1.1, 1.4	3.8, 4.4, 5.3	1, 1.5, 1.8
Average responses	$\widetilde{av}_j$	3.12, 3.64, 4.18	3.26, 3.58, 4	4.28, 4.6, 5.2	3.32, 3.64, 4	2.98, 3.34, 3.84
Crisp value	$\kappa(\widetilde{av}_j)$	3.645	3.605	4.67	3.65	3.375

The defuzzification method that was used for a triangular fuzzy number -$\tilde{A} = (a_1, a_2, a_3)$- in this case study was as follows:

$$\kappa(\tilde{x}) = \frac{a_1 + 2 \times a_2 + a_3}{4} \tag{16}$$

Table 9. Negative distance from average (nda) and positive distance from average (pda).

Alternatives		pda				
		C_1	C_2	C_3	C_4	C_5
Brick façade	A1	-0.19, 0.21, 0.49	-0.78, -0.55, -0.38	0.69, 0.92, 1.01	-0.82, -0.72, -0.58	-0.37, -0.07, 0.24
Stone façade	A2	1.08, 1.36, 1.61	-0.67, -0.44, -0.21	0.34, 0.56, 0.75	-0.71, -0.42, -0.20	-0.66, -0.40, -0.08

Coatings cement facade	A3	-0.65, -0.29, 0.02	1.22, 1.39, 1.59	-0.21, -0.02, 0.30	1.32, 1.47, 1.56	1.44, 1.68, 1.78
Composite facade	A4	-0.82, -0.56, -0.14	0.03, 0.31, 0.51	-0.90, -0.69, -0.47	0.08, 0.29, 0.54	-0.84, -0.69, -0.50
Curtain wall	A5	-0.87, -0.72, -0.53	-0.83, -0.72, -0.49	-0.90, -0.77, -0.62	-0.79, -0.61, -0.39	-0.84, -0.52, -0.17

Alternatives		**nda**				
		C_1	**C_2**	**C_3**	**C_4**	**C_5**
Brick façade	A1	-0.49, -0.21, 0.19	0.38, 0.55, 0.78	-1.01, -0.92, -0.69	0.58, 0.72, 0.82	-0.24, 0.07, 0.37
Stone façade	A2	-1.61, -1.36, -1.08	0.21, 0.44, 0.67	-0.75, -0.56, -0.34	0.20, 0.42, 0.71	0.08, 0.40, 0.66
Coatings cement facade	A3	-0.02, 0.29, 0.65	-1.59, -1.39, -1.22	-0.30, 0.02, 0.21	-1.56, -1.47, -1.32	-1.78, -1.68, -1.44
Composite facade	A4	0.14, 0.56, 0.82	-0.51, -0.31, -0.03	0.47, 0.69, 0.90	-0.54, -0.29, -0.08	0.50, 0.69, 0.84
Curtain wall	A5	0.53, 0.72, 0.87	0.49, 0.72, 0.83	0.62, 0.77, 0.90	0.39, 0.61, 0.79	0.17, 0.52, 0.84

Table 10. Weighted positive and negative distances from average and related normalized values.

Alternatives		**sp**	**nsp**	**sn**	**nsn**
Brick facade	A1	-7.67, -2.98, 0.98	-0.58, -0.22, 0.07	-1.66, 2.98, 10.24	0.28, 0.79, 1.11
Stone facade	A2	3.42, 8.35, 13.16	0.26, 0.63, 0.99	-12.91, -8.35, -1.33	1.09, 1.59, 1.91
Coatings cement facade	A3	5.73, 12.93, 21.32	0.43, 0.98, 1.61	-14.88, -12.93, -10.46	1.73, 1.91, 2.04
Composite facade	A4	-8.34, -4.09, 3.00	-0.63, -0.31, 0.23	-2.01, 4.09, 9.53	0.33, 0.712, 1.14
Curtain wall	A5	-15.76, -14.20, -10.81	-1.19, -1.07, -0.82	8.85, 14.20, 19.66	-0.38, 0.002, -2.77

Table 11. Alternatives' scores and rankings.

Alternatives		$\widetilde{as}_i$	**Ranking**
Brick facade	A1	0.2526783	3
Stone facade	A2	1.0861673	2
Coatings cement facade	A3	1.4497902	1
Composite facade	A4	0.2341943	4
Curtain wall	A5	-0.519481	5

5. Conclusion

As mentioned above, a building façade is the first barrier resisting waves and quivers from an explosion, and it plays a determining role in decreasing a building's vulnerability and human casualties. Thus, in this research, we tried to assess various widely used materials in this part of a building (due to effective indices). To do so, 5 out of 10 indices were considered, including reducing an explosion's effect, debris removal capability, resistance to fire capability, reconstruction capability, and implementation costs. In this regard, a list of 10 important indices (as a criteria list) was developed based on expert opinions and was screened using a fuzzy Delphi technique to find the five most important indices in the rest of a façade assessment. According to the screening phase results, reducing an explosion's effect had the most influence on selecting the proper façade, and then implementation costs were placed in the next rank. As a consequence of the screening phase, an assessment of different façade materials was practiced using fuzzy EDAS. Based on the results, a "coatings cement facade" was recognized as the best alternative to building a façade to enhance resistance to an explosion wave. In addition, a "stone facade" was selected as the second best material, with a minimal difference in the importance factor. However, other alternatives were steeply lower in importance and are not recommended for use as façade materials in blast-resistant buildings. The proposed methodology can be used to evaluate other materials in other case studies, based on different project environments, available options, and other standards and specifications according to a project's obligations.

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References

1. Pourirahim, A.A., Bitarafan, M., Lale Arefi, S. Evaluation of Types of Shapes of Building Roof Against Explosion. *IACSIT Int. J. Eng. Tech.* **2013**, *5*, 1–4; doi:10.7763/IJET.2013.V5.498
2. Araghizadeh, M. Requirements and Architectural Design Considerations for Bureau Buildings from Passive Defense Point of View. Master Thesis, Malek Ashtar University: Tehran, Iran, August 2011.
3. Gebbeken, N., Döge T. Explosion Protection—Architectural Design, Urban Planning and Landscape Planning. *Int. J. Protect. Struct*. **2010**, *1*, 1–21.
4. Barakat, M., Hetherington, J.G. New architectural forms to reduce the effects of blast waves and fragments on structures, Editors: Talasdilis, D.G., Brebbia, C.A., Jones, N., Structures under Shock and Impact V. *Comput. Mechan. Publ.* **1998**, *32*, 53–62.
5. Mojtahed Pour, M. The influences of the shape of instruction on stress distribution from eruptive loading, University of Khalije Fars, The Educational Research Institution of Defensive Crafts, Engineering Faculty. 2009.
6. Luccioni, B.M., Ambrosini, R.D., Danesi, R.F. Analysis of building collapse under blast loads. *Eng. Struct.* **2004**, *26*, 63–71; doi:10.1016/j.engstruct.2003.08.011
7. Nakhaei J., Bitarafan M., Lale Arefi S., Kapliński O. Model for rapid assessment of vulnerability of office buildings to blast using SWARA and SMART methods (a case study of swiss re tower). *J. Civil Eng. Manag.* **2016**, *22*, 831–843; doi:10.3846/13923730.2016.1189457
8. Nakhaei J., Bitarafan M., Lale Arefi S., Choosing the best urban tunnels as safe space in crisis using AHP method: a case study in Iran. *J. Arch. Urban.* **2015**, *39*, 149–160; doi:10.3846/20297955.2015.1056439
9. Bitarafan, M., Hosseini, S.B., Sabeti, N., Bitarafan, A. The architectural evaluation of buildings' indices in explosion crisis management. *Alexandria Eng. J.* **2016**, *55*, 3219–3228; doi:10.1016/j.aej.2016.08.015
10. Bitarafan M., Hosseini S. B., Abazarlou S., Mahmoudzadeh A. Selecting the optimal composition of architectural forms from the perspective of civil defense using AHP and IHWP methods. *Arch. Eng. Design Manag.* **2015**, *11*, 137–148; doi:10.1080/17452007.2013.802982
11. Hosseini, S.B., Bitarafan, M., Hashemi-Fesharaki, S.J., Norouzian-Maleki, S. The Role of Basic Forms Buildings in Explosion Protection, International Journal of Science and Advanced Technology, **2012**, *2*, 47–50.
12. Bitarafan, M., Hosseini, S.B.; hashemi-fesharaki, S.J., Esmailzadeh, A. Role of architectural space in blast-resistant buildings. *Front. Arch. Res.* **2013**, *2*, 67–73; doi:10.1016/j.foar.2012.11.003
13. Hosseini S. T., Lale Arefi S., Bitarafan M., Abazarlou S., Zavadskas E. K. Evaluation types of exterior walls to reconstruct Iran earthquake areas (Ahar Heris Varzeqan) by using AHP and fuzzy methods. *Int. J. Strat. Prop. Manag.* **2016**, *20*, 328–340; doi:10.3846/1648715X.2016.1190794
14. FEMA 426 Reference Manual to Mitigate Terrorist Attacks Against Buildings, December 2011. https://www.dhs.gov/xlibrary/assets/st/st-bips-06.pdf
15. Chang, P.T., Huang, L.C., Lin, H.J. The Fuzzy Delphi method via fuzzy statistics and membership function fitting and an application to the human resources. *Fuzzy Sets Syst.* **2000**, *112*, 511–520.
16. Keshavarz Ghorabaee, M., Zavadskas, E.K., Olfat, L., & Turskis, Z. Multicriteria inventory classification using a new method of evaluation based on distance from average solution (EDAS). *Informatica* **2015**, *26*, 435–451.
17. Keshavarz Ghorabaee, M., Zavadskas, E.K., Amiri, M., Turskis, Z. Extended EDAS Method for Fuzzy Multi-criteria Decision-making: An Application to Supplier Selection. *Int. J. Comput. Commun. Contrl.* **2016**, *11*, 358–371.
18. Kahraman, C., Keshavarz Ghorabaee, M., Zavadskas, E.K., Cevik Onar, S., Yazdani, M., Oztaysi, B. Intuitionistic fuzzy EDAS method: an application to solid waste disposal site selection. *J. Environ. Eng. Landscape Manag.* **2017**, *25*, 1–12.
19. Keshavarz Ghorabaee, M., Amiri, M., Zavadskas, E.K., Turskis, Z., Antucheviciene, J. A Dynamic Fuzzy Approach Based on the EDAS Method for Multi-Criteria Subcontractor Evaluation. *Information* **2018**, *9*, 68; doi:10.3390/info9030068.
20. Keshavarz Ghorabaee, M., Amiri, M., Zavadskas, E.K., Turskis, Z., Antucheviciene, J. A new multi-criteria model based on interval type-2 fuzzy sets and EDAS method for supplier evaluation and order allocation with environmental considerations. *Comput. Indust. Eng.* **2017**, *112*, 156–174.
21. Keshavarz Ghorabaee, M., Amiri, M., Zavadskas, E.K., Antucheviciene, J. A new hybrid fuzzy MCDM approach for evaluation of construction equipment with sustainability considerations. *Arch. Civil Mechan. Eng.* **2018**, *18*, 32–49.

22. Schitea, D., Deveci, M., Iordache, M., Bilgili, K., Zeki Akyurt, I., Iordache, I. Hydrogen mobility roll-up site selection using intuitionistic fuzzy sets based WASPAS, COPRAS and EDAS. *Int. J. Hydr. Energy* **2019**, *44*, 8585–8600.
23. Stević, Ž., Vasiljević, M., Puška, A., Tanackov, I., Junevičius, R., Vesković, S. Evaluation of suppliers under uncertainty: a multiphase approach based on fuzzy AHP and fuzzy EDAS. *Transport* **2019**, *34*, 52–66.