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Preliminary communication

Evaluation of Elements for Selection of Optimal Solution for Facility Passive Protection from the Fire Spread over Facade

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Abstract: Fire protection of facilities is basically based on passive and active form. Given that active forms have a limited role in the early stages of fire, the decisive role in preventing the spread of fire, until the arrival of emergency firefighting units, have elements of passive protection at the facility. The topic of this paper is facades in residential buildings and their role in spreading fires throughout the building. The aim of this paper is to design one of the possible models for choosing the optimal façade shape (or the facility), which would passively prevent the transmission of fire over the facade. For these purposes, an analysis of key aspects was performed, which, in addition to fire resistance, considered seismic resistance and energy efficiency, both dependent on the shape of the facility. The obtained results are valorized through a quality scale, based on which is determined whether the solution is bad, acceptable, satisfactory, or good. This model contributes to a quality and controlled design process, because the concept of a facility, that meets the requirements of modern construction, is obtained at an early stage. The practicality of this model is reflected in the fact that, on the one hand, in the design phase it allows to bring more variant solutions at the same qualitative level, and on the other hand it is applicable to already constructed facilities, which indicates shortcomings and possibilities of their reconstruction.

Keywords: facility geometry; façade elements; fire factors; flashover; passive fire protection; quality scale

1 INTRODUCTION

Fires on facilities are a constant danger, with consequences, measured by the loss of human lives and great material damage. Even today, it is equally present, regardless of the level of technological development, as evidenced by numerous reports from national fire agencies [1]. The subject of this research are residential buildings and their fire resiliency, observed from the aspect of spreading fire over the facade, around the building and towards the immediate environment. The goal is to enable easy selection of optimal solutions for facilities, with a passive form of fire protection over the facade, taking into account their shape. In order to choose the optimal facade shape, in addition to passive fire protection, seismic resistance was taken into account, as well as energy efficiency, which depends on the facility shape. Based on that, a model for the selection and evaluation of the facade shape was formed, which provided passive facility protection from the spread of fire over the facade.

Based on the adopted model, the evaluation of one residential building, built in 1965, and two modern residential buildings, with a new concept of passive fire protection across the façade, was performed.

2 FIRE SPREADING OVER FACADE

The spread of fire over facade is a phenomenon that is constantly being investigated in order to establish the most favorable protection mechanism in the conditions of its occurrence and spread, with the aim of effectively reducing the action consequences. The goal is to reduce the conditions of fires by applying modern means and technologies, and thus reduce the loss of human lives, as well as material damage. There are external [2] and internal fire causes, that are transmitted to the entire facility over facade. The fire causes in a facility, according to the statistics [3], are kitchens, heaters and electrical appliances.

Indoor fire can reach its highest intensity, thanks to the high temperature of smoke layer (400-600 °C), as well as high radiation (20 kW/m^2). During this event flammable gases burn in a short time, and this phenomenon is known as flare-up or flashover [4]. In order to prevent the penetration of fire on a facade, the first condition is to relieve the interior space or even prevent the formation of a smoke layer and high radiation [5]. In the initial phase, the fire can be localized with active fire-fighting measures - sprinklers and hand-held fire extinguishers. With the emergence of flashover, active control measures are no longer useful, so passive protection measures, such as separation and fire barriers, become important in preventing or limiting structural breakage or the spread of fire.

During the flashover, fire is spreading through a building interior and towards the facade. Openings on the façade represent a weak spot, a place where fire penetrates to the outside environment, primarily windows and doors (balcony or French window), because such elements are the most common ones. Furthermore, depending on the flame energy and the air flow from a building, the fire spreads along the facade - vertically and horizontally and towards the environment.

According to [6], fire directions when the facade is in the flame, are as follows:

- Bypassing of fire compartments via perimeter wall-deck joint;
- Bypassing fire compartments via air gaps and breaking windows;
- Fire spread on façade as required to pass façade tests.

One of the basic requirements of fire protection is the correct choice of construction materials. Fire properties of building materials include: combustibility, flammability, flame spread rate, ability to generate smoke, toxic gases and thermal power. Proper use of building materials depends on knowledge of these properties.

Research, focused on the behavior of facades in the event of fire, is mainly reduced to the analysis of applied materials in their structure (the example of the Scandinavian countries [7]). However, they are not the only elements of passive facility protection. When it comes to the external fire transmission, through the facade, in addition to (fire) qualities of the applied materials, the important aspects are the facade structure, geometry and arrangement of facade openings. As elements of the overall inertia assessment (slowness) of fire spread over the facade, they need to be applied in the process of total (fire, energy, construction) rehabilitation of existing buildings, and in programming the content of passive fire protection in designing new buildings.

3 PASSIVE PROTECTION FORMS OF THE FACADE AGAINST FIRE

In Serbia, legal regulations have adopted provisions defined by the *Rulebook on technical standards for the protection of high-rise buildings from fire* [8]:

1. The building facade must be constructed in a way that fire cannot be transmitted from one floor to another (by appropriate vertical breaking distance (Fig. 1) or cantilever parts of the structure, at the level of the mezzanine structure, the minimum length and width, which are defined by this Rulebook).
2.

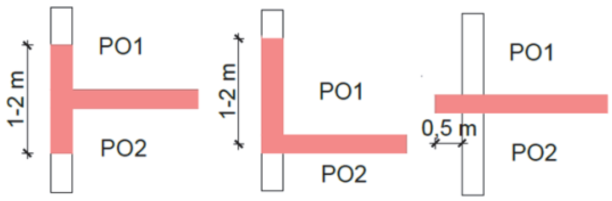


Figure 1 Elements of breaking distance according to [8]

3. The horizontal spread of fire over the facades is prevented by the horizontal breaking distance, which defines the conditions for two buildings cases: simple and complex shapes.
4. Thermal insulation (T.I.) external walls layers and self-supporting prefabricated facade panels must be made of non-combustible materials.

Complete or partial wall curtains must be stable in fire and constructed in such a way to prevent the transmission of fire.

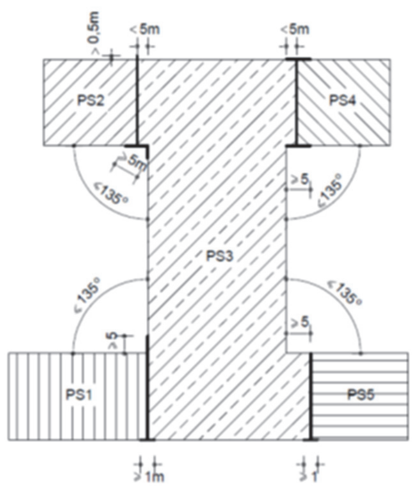


Figure 2 Horizontal interrupted distance (bold line) for objects with a dispersed (complex) plan [8]

All breaking distances must have fire resiliency with a characteristic of at least E1 90, according to a specific standard for external walls, to prevent the transmission of fire on the building facade (regardless of the type of facade wall: masonry wall, panel, glass, etc.). The blinds on the windows outside need to be made of a non-combustible material.

However, according to [2] it can be concluded that the vertical breaking distance, in the range of 1-2 m, is not appropriate, and thus the lower value must be significantly shifted, or protective barrier must be set (e.g., console), length min l = 1.0 m [9, 10].

3.1 Parametric Analysis

For the architectural design of a facade, from the point of view of passive fire protection, one of the starting assumptions of this paper is that it is not enough to consider the facade as a separate part of the facility, but the facade as an important part of its whole. Therefore, the shape of a facade is a shape function (volume) of the building, but also the facade structure (content of the layers) is a function of the facade shape. Each of these levels is analyzed, evaluated and validated from the following aspects: constructions and structures (facade walls), energy efficiency and fire resiliency. The point scale is from 1 to 10, with a range of values and quality:

- from 1-3 bad,
- from 4-5 satisfactory,
- from 6-7 good,
- from 8-9 very good,
- 10 excellent.

Point ranges "from-to", within one value group on the scale (e.g. 6-7 good) indicate that the evaluated groups contain subtypes that vary in quality. If some aspects are assessed as bad, then the whole concept of the facility is rejected. This is typical for the analysis and evaluation of existing facilities, which indicates bad places on a facility, that need to be repaired.

3.1.1 Facility Shape

<u>*Structure* (S)</u>: Facilities of simple structure and foundations, axisymmetric, regular configuration with relatively uniform distribution of mass and stiffness, are characterized by a favorable dynamic structure response, and continuous elements, resistant to seismic force. However, in the case of uneven distribution of strength or stiffness and discontinuity of the structural system, irregularities in the structure can occur [10-13]. Facilities of more complex configuration [14, 15] and foundations require more complex constructive solutions, more materials, labor, construction logistics and time [16-19].

<u>*Energy Efficiency* (EE)</u>: Good facility properties of simple basis are conditioned by (smaller) number of angles, area and volume of the facility (A/V). The highest EE quality is achieved by a circular base facility, smaller surface area and higher facility height [20]. Greater shape irregularity and elongation are less desirable, because of the larger area under temperature influences. According to [13], following the circular base, the square base is the most favorable. Bases with the smallest angles are the least energy losers [21]. In the paper [22], an example of U-base facility is presented. All facility parts with overhang must be thermally insulated [23].

Fire Resiliency (FR): Transmission and fire spread over facade are conditioned by several factors, as follows: a) the layout of openings (windows), which is not appropriate, even according to current regulations; b) geometry of the facade and elements of the facade (on the part of the floor overhang - vertical fire barrier) and c) applied materials for facade finishing (combustible T. I. materials are often the cause of fire spread throughout the facility) [24]. Due to the lack of barriers on the facade, the fire transmission over the facade is simple [25, 26]. When the shapes are more fragmented, if each part of the building is recognized as a separate fire sector, the fire spreads separately along the facade [27]. From the other perspective, excessive fragmentation causes the accumulation of users in the facility, which is undesirable during evacuation [28].

3.1.2 Facade Elements

Openings - windows and doors

Structure (S): Window surfaces, in relation to solid walls, are significantly more expensive part of the facade partition, especially when the surface under the glass is larger, in relation to the standard parapet dimensions. Therefore, the organization of windows, as a grouping of individual elements, is more economically advantageous than window strips. Openings with a frame complicate the execution of works on a facade, especially if they are performed simultaneously with it. It is similar with the window barriers. They can be performed simultaneously with and subsequently to the facade.

Energy Efficiency (EE): Large area under the glass is thermally the weakest place on the facade. This is especially present in older facilities. Reduced surface under glass, with higher wall mass is the more advanced energy-efficient solution. More favorable solution is when the window gaps are larger. If openings with the frame are made at the same time as the facade, it is necessary to secure them from the appearance of cold bridges.

Fire Resiliency (FR): Windows represent a black fire spot, especially in older facilities. Thus, in the case of window strips, the effects of fire are expressed in both directions, horizontally and vertically of the facade. Fire characteristics vary from the inter-window distance horizontally, and especially vertically, because of the easier fire transmition. A favorable solution for preventing the fire transmission over facade, is also with the windows in the irregular line vertically, for the entire floor. Also, an effective element of passive fire protection, through the openings on the facade, is a window with a frame or barrier.

Loggias and Balconies

Structure (S): Loggias are an element of the ceiling in contour of the floor, whose execution does not require additional work (such as for cantilever overhangs at the balcony). Framing can be done simultaneously and subsequently, with the execution of the loggia/balcony elements.

Energy Efficiency (EE): Loggia is a space protected by walls on three sides, so the effect of solar radiation is favorable: protection in summer and sunshine in winter. Balcony is a surface element whose construction needs to be thermally insulated from all sides, due to the appearance of thermal bridges. In loggias and balconies, EE is further improved by glazing - the greenhouse effect.

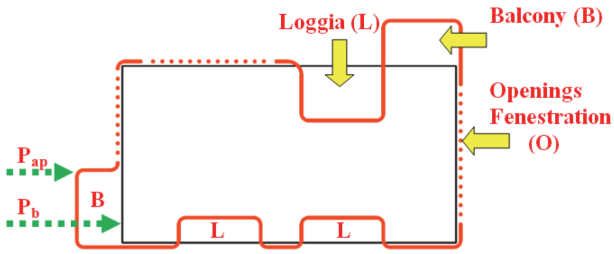


Figure 3 The usual outline residential buildings: Pap - a complex shape compilation of area onto cantilevers or balconies; Pb - a simplified shape based on geometric forms

Fire Resiliency (FR): Loggias and balconies are elements of good passive fire protection, the effect which increases, with the increase of their depth. Moreover, the effect of protection is increased by adding a frame. Due to the cold bridges, balconies must be insulated with T. I., made of non-combustible and non-flamable material (e.g. mineral wool).

3.1.3 Facade Structure

Structure(S): Non-insulated walls do not have the cost of performing thermal protection. This refers to facilities built at a time when there was no legal obligation for the thermally insulated facilities in general. Insulated walls vary depending on the type of thermal insulation. ETICS facades are the simplest to perform, but mechanically the most sensitive. If T.I. is performed with styrofoam, it does not require a vapor barrier [29]. For sandwich walls with mineral wool insulation, it is necessary to add a layer for vapor barrier. The exterior cladding can be plastered or made of brick facade. With the ventilated facade, the vapor barrier is not installed, but it is necessary to increase the layer of thermal insulation. ETICS facades are optimal for thermal reconstructions of facilities.

Energy Efficiency (EE): Non-insulated, thermally unfavorable walls, must be T. I. in the reconstruction of existing and construction of new facilities according to current regulations. All types of insulated facades, harmonized with the standard, meet thermal conditions.

Fire Resiliency (FR): Favorable if insulated with non-flammable and non-combustible material. Thermoplastic insulation is a fire black point, because the flame spreads vertically upwards and downwards, with combustible solutions [29]. The most rational solution is when thermoplastic and stone wool materials are combined (Fig. 4b).

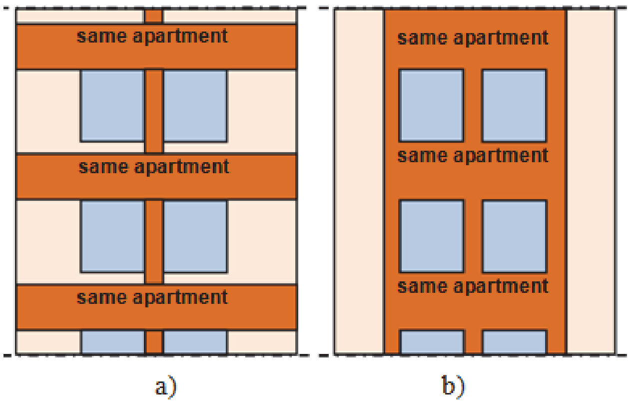
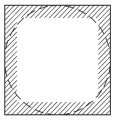
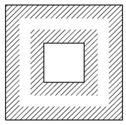
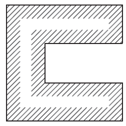
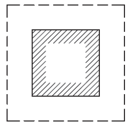
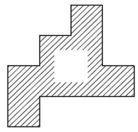
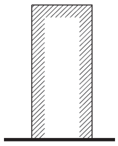
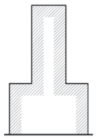
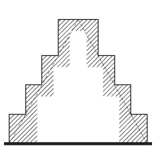
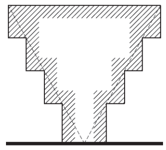
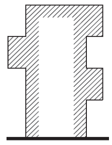
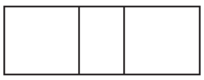
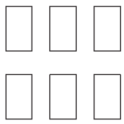
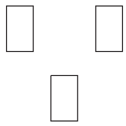
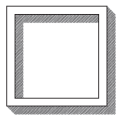
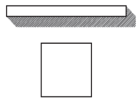
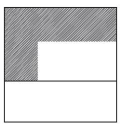
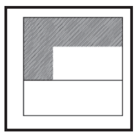
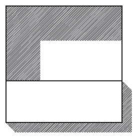
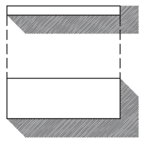
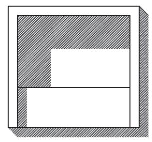
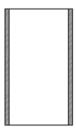
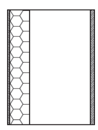
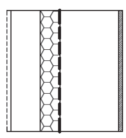
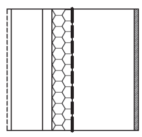
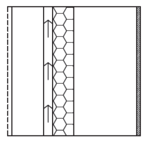


Figure 4 The TI non-combustible covering: a) experimentally tested [33]; b) author's suggestion [24]

Table 1 Analysis (assessment) of building elements based on aspects of applied structure, energy efficiency and fire resistance (inertia)

A. Facility Shape					
1. Basis	1.1. Simple 	1.2. Atrium 	1.3. Semi-atrium 	1.4. Retracted Ground Floor 	1.5. Asymmetric Shape 
S	10	8	L = 5 U = 6 T = 7 H = 8.	1-5	1
EE	10	8	L = 5 U = 6 T = 7 H = 8.	7-9	1
FR	7	8	8	7-9	1-3
2. Side look	2.1. 4-Prism/Roller 	2.2. Sitback 	2.3. 4-Stepped Pyramid 	2.4. 4-Inverted Pyramid 	2.5. Asim. Mass Overhangs 
S	10	8	4-6	1-5	5-8
EE	10	8	4-6	3-8	5-8
FR	7	9	7-10	7-10	7-10
B. Façade Elements					
1. Openings (Windows*)	1.1. Continuous Stripe 	1.2. Arranged Grouping 	1.3. Irregular Grouping 	1.4. Frame/Screen 	1.5. Window Barrier 
S	3-8	5-8	8-10	8	8
EE	1-8	5-10	6-10	8	9
FR	1-5	3-10	10	10	9
2. Loggias + Balconies	2.1. L-Open/Glazed 	2.2. L+Frame-Open/Glazed 	2.3. L+B-Open/Glazed 	2.4. B-Open/Glazed 	2.5. B+Frame-Open/Glazed 
S	10	8	8	8	8
EE	9	7-9	8	3	7
FR	9	10	10	9	10
C. Facade					
Structure	1. Without T.I. 	2. Compact 	3. Sandwich Wall 	4. With Cavity 	5. Ventilated 
S	10	10	9	8	8
EE	0	10	10	10	10
FR	10	0 / 10	10	10	0 / 10

* Doors as well, if present on the façade in the form of French window or within loggia/balcony

Air layer in the ventilated facade, above the openings (windows, doors) must have a built-in fire barrier (Fig. 5) that conducts air, while, in case of fire, blocks the entrance of the flame.

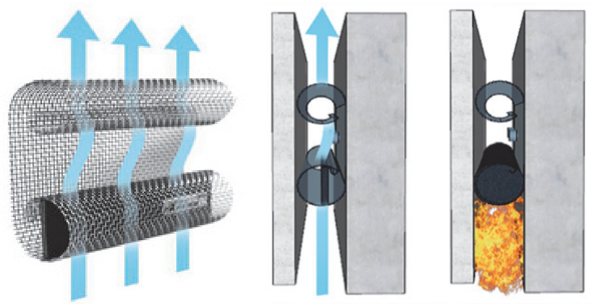


Figure 5 The barrier element and the acting mechanism [30]

4 EVALUATION DESIGN SOLUTIONS OF FIRE-RESISTANT FACADEDES - EXAMPLES

All analyzed elements - facility shape, facade elements and facade structure, as well as their evaluation, based on the three adopted aspects, are shown in Tab. 1.

The value (v_n) is the total value of the building shape, facade elements and structure (layers) of the facade and is obtained by summing the values of aspects: V_S - structure, V_{EE} - energy efficiency, V_{FR} - fire resistance, for each of the levels. Value of the aspects was obtained by evaluating five selected shapes for all three levels (Tab. 1). Value scales were created based on the analysis of selected forms, thus based on complexity in performance and efficiency during use.

When evaluating the solution, it is possible for several elements to appear within one group (e.g., the facility with loggias and balconies), so the average value is adopted. Category is defined on the basis of the quotient of the total value of each of them (v_n) from Tab. 1 and their total maximum value (V).

$$K = \frac{\sum v_n}{\sum V} \times 100 \qquad (1)$$

where: K - qualitative coefficient; $v_n = V_S + V_{EE} + V_{FR}$; V - max value of the analyzed aspect. Highest value of the coefficient is one hundred (100).

Table 2 Solution analysis

<table>
<tr><td colspan="5">A facility picture or 3D presentation</td></tr>
<tr><td></td><td>Structure (S)</td><td colspan="2">Energy Efficiency (EE)</td><td>Fire Resiliency (FR)</td></tr>
<tr><td>Object Form</td><td>Layout:
Side:</td><td colspan="2">Layout:
Side:</td><td>Layout:
Side:</td></tr>
<tr><td>Facade Element</td><td>Openings:
L/B:[1]</td><td colspan="2">Openings:
L/B</td><td>Openings:
L/B</td></tr>
<tr><td>Facade Structure[2]</td><td></td><td colspan="2"></td><td></td></tr>
<tr><td>Individual sum</td><td>$\sum V_S$</td><td colspan="2">$\sum V_{EE}$</td><td>$\sum V_{FR}$</td></tr>
<tr><td>$\sum V$:</td><td colspan="4"></td></tr>
<tr><td>V(max)</td><td colspan="4"></td></tr>
<tr><td>K</td><td></td><td></td><td></td><td></td></tr>
<tr><td>R</td><td>0-50</td><td>51-75</td><td>76-90</td><td>91-100</td></tr>
<tr><td>Category</td><td>Bad</td><td>Acceptable</td><td>Satisfactory</td><td>Good</td></tr>
</table>

L - Loggia, B - Balcony
[1] L/B = average value, when both elements are present on the facade
[2] Facade specificity, e.g. precast + thermal insulation

Obtained value is compared with the values that define the quality level of the solution:
- from 0-50 bad,
- from 51-75 acceptable,
- from 76-90 satisfactory,
- from 91-100 good.

In Tab. 2 is presented the quality scale, that evaluates the solution. The proposed scale shows that a high coefficient (76-100) is required for quality solutions and refers to new design solutions. Values from 0-75 refer to the analyzed existing facilities, where those, with a coefficient above 51, can be registered under "acceptable", without mandatory reconstruction.

4.1 Sample 1 - Evaluation of the Building Since 1965

Sample 1 represents the building inhabited in 1965. It was built in the prefabricated skeletal system. The parapets are prefabricated AB sandwich, with window strips, sash on sash, classically glazed, without thermal package and with a fixed part between two windows, 30 cm wide, with thichness of d = 5 cm. This building is also made with loggias and balconies. Balconies are with depth of d = 98 cm.

Table 3 The prefabricated building since 1965. (Photo: by authors)

	Structure (S)	**Energy Efficiency (EE)**	**Fire Resiliency (FR)**
Object Form	Layout: 10 Side: 10	Layout: 10 Side: 10	Layout: 7 Side: 7
Facade Element	Openings: **3** L/B 10/8 = 9	Openings: **1** L/B 9/8 = 8,5	Openings: **1** L/B 9/9 = 9
Facade Structure[2]	9	10	10
Individual sum	41	39,5	34
$\sum V$:	114,5		
V(max)	150		
K	**76 (satisfactory)**		

According to the coefficient value (K = 76) in the section „Category“ satisfies, but due to poor grades, the facade elements - windows do not satisfy, the building is poor in the category, and reconstruction is necessary.

4.2 Sample 2 - Newly Designed Building

Combination 1 - Facility 2

Facility 2 (Tab. 3) was built in 2011. Building shape is of the simple base. The balconies are expressive, oriented towards the sunny side, with vertical barriers. The windows on the sunny side have frames.

Windows on the north side are not framed, thus are with large gaps in both directions (vertical and horizontal).

Table 4 A well-adjusted object plastic and openings toward fire safety requirements (possibly by accident) [31]

	Structure (S)	Energy Efficiency (EE)	Fire Resiliency (FR)
Object Form	Layout: 9 Side: 10	10 9	10 10
Facade Element	Openings: 8	10	10
Facade Structure[1]	10	10	10
Individual sum	38	40	40
∑*V*:	116		
***V*(max)**	120		
K	**97 (good)**		

[1] ETICS - Combined min.wool/styrofoam (Fig. 4)

Combination 2 - Facility 3

Facility 3 (Tab. 4) was built in 2017. It is based on the concept of a simple shape and basis building. The openings on the facades are in the shape of a French window and balcony, cut in the horizontal direction, forming a zigzag arrangement on the facade. Both the windows and the balconies are framed.

Table 5 Irregular and framed openings [32]

	Structure (S)	Energy Efficiency (EE)	Fire Resiliency (FR)
Object Form	Layout: 9 Side:10	10 10	10 10
Facade Element	Openings: 8	9	10
Facade Structure[1]	10	10	10
Individual sum	37	39	40
∑*V*:	118		
***V*(max)**	120		
K	**98 (good)**		

[1] ETICS - Combined min.wool/styrofoam (Fig. 4)

4.3 Comments on the Obtained Results

Facility 1 (Tab. 1) is relatively highly rated (76), due to the highly valued aspects of building shape and facade structure. However, the element of the facade - the openings are low-valued, in the form of continuous strips, with great potential for fire transmission over the facade, in both directions. Low-scoring windows, as black fire points, classify Facility 1 in the category of bad buildings, with the necesity to repair weak spots.

Facilities 2 and 3 are with a close sum of points (97), although initially intended as two different concepts. The only similarity is with the first element of analysis (Facility Shape). Such facilities are more expensive to build, but it is economically and security-wise justified to have an energy-efficient and fire-resistant facility (specifically the transmission of fire over the facade).

Example 1 showed that for a good quality solution it is necessary to emphasize and point out the elements with a small number of points, because these are weak points that need to be repaired, from the aspect of passive fire protection. Such a poorly assessed aspect (there can be two or all three) totally disqualifies such facility (in this case an existing building) or the offered solution. Practice has shown that simple solutions are the most economical and safest ones. However, practice has also shown that neither users nor designers are satisfied with this principle, which complicates the entire process of choosing the facility (and facade) with optimal passive protection against fire transmission over the facade.

5 CONCLUSION

The presented research is based on the assumption that passive protection is a key form of protection against a blazing fire until the moment of firefighter intervention, specifically protection against the transmission of fire over the facade. Facade cannot be analyzed as an isolated segment, but as an indivisible part of the building, formed of elements, with a specific, often complex structure.

Analysis of the facade design of multi-storey buildings, from the aspect of passive protection against fire transmission over the facade, must include the design of the building, as well as the aspect of seismic resistance of the building, with thermal protection. All criteria must be met, in other words, none of the observed criteria can be unsatisfied.

The best solutions are often the most expensive, but with the right choice, enough quality and economical solutions they can be achieved.

The proposed evaluation model of achieved solutions for passive protection against fire transmission over the facade, while satisfying seismic resistance and thermal protection, includes quantification of solutions, according to these three aspects.

The proposed model, primarily from the aspect of passive fire protection, but with full respect to the a-seismic design of the building and thermal protection, can be applied to constructed facilities, as well as to ones in the design phase. The next step is to transfer this model to the appropriate computer application (android, etc.), which makes the process of modelling the facade much faster, and more comfortable for designers.

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