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Identification of factors shaping tender prices for lightweight curtain walls

Key words: price-creating factors, aluminum-glass facade, ventilated facade, lightweight curtain wall

Introduction

Successful completion of a construction project means that its completion has been completed within the assumed budget, at the scheduled time, in accordance with the expected quality, and taking into account all investor requirements. In the literature, many studies can be found regarding the analysis of construction projects due to their costs (Juszczyk, Leśniak & Zima, 2018; Leśniak & Juszczyk, 2018; Leśniak & Zima, 2018; Wieczorek, Plebankiewicz & Zima, 2019), time (Ibadov & Kulejewski, 2015; Krzemiński, 2017), organizational aspects (Hoła, 2015; Kozlovska, Mackova & Spisakova, 2016; Lendo-Siwicka, Połoński & Pawluk, 2016; Nowotarski, Pasławski & Matyja, 2016; Grzyl, Miszewska-Urbańska & Apollo, 2017; Nowogońska & Cibis, 2017; Hanak & Korytarova, 2018), safety issues (Hoła & Szóstak, 2015), or the use of innovative solutions in construction filed (Mrówczyńska, 2011; Kapliński, 2018). Yet, it is the calculation of costs that is one of the most important aspects of construction projects, both from the investor's and contractor's point of view. The correct estimation of the costs of executing the object of the order allows to reduce the risk of possible disputes and failure of a given construction project. Already in the project preparation phase, the investor estimates the costs indicatively on the basis of predesign analyses and feasibility studies. In addition, the development of a conceptual design allows to determine the amount of financial expenditures that the investor will have to incur during the implementation of the planned project, already at the stage preceding the basic design work (Kasprowicz, 2007). Through a thoroughly prepared cost calculation, the contractor can include the full cost of building or construction works, taking into account

the expected level of profit or the impact of potential risk. The calculation made by the contractor becomes, therefore, the tender price and it provides information whether the implementation of a given investment for a given investor will be profitable.

The technical basis for the cost calculation is project documentation (including concept, construction and execution). The design documentation contains a complete set of graphical and descriptive information that characterizes the construction object, while the degree of its detail and accuracy is significantly reflected in the investment costs (Juszczyk, Kozik, Leśniak, Plebankiewicz & Zima, 2014).

Basing on an analysis of a large amount of design and cost estimate documentation as well as on theoretical and professional knowledge, the authors attempted to identify the factors that may shape the tender price for the construction of lightweight curtain walls. The paper describes the factors that can affect the cost of facade implementation in the lightweight outer casing technology. Moreover, the paper presents the authors' method of estimating the tender price for lightweight curtain walls, incorporating the factors identified in the work, including basic construction data, the type of material used and technological assumptions.

Lightweight curtain walls – characteristics of the subject of research

Public buildings of the 21st century are characterized by an original form and individual character. They attract attention with their appearance, but also with modernity and lightness of construction solutions. The use of light curtain walls allows to forget about heavy, concrete buildings and the light outer casing of the facade shapes the contemporary tastes, being responsible for the originality and boldness of architectural forms.

The PN-EN 13830:2005 standard defines a curtain wall as the outer casing of a building with a frame structure, usually made of metal, wood or PVC-U, consisting of vertical and horizontal structural elements, joined together and attached to the supporting structure of the building. According to the classification adopted in publication (Urbańska-Galewska & Kowalski, 2016), light curtain walls are divided into the following:

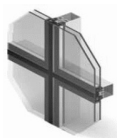
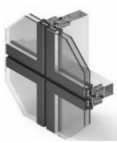
– single-layer, which are made of aluminum (steel) sheet, glass or plastic plates,
– multi-layer, constructed as ventilated or non-ventilated ones,
– glass and metal, among which pole-bolt, structural and semi-structural walls are distinguished.

To identify and analyse the factors affecting the implementation costs of a lightweight curtain wall, the authors chose glass-metal facades (aluminum-glass facades) and ventilated multi-layer facades. Both types of facades will be characterized below.

Aluminum-glass facades

Aluminum and glass facades are one of the most common types of lightweight curtain walls. They are built from aluminum sections, and the spaces between the aluminum construction is filled with glass. Aluminum-glass facades can be divided into post and beam, structural and semi-structural facade systems. Table 1 presents the characteristics of each system.

TABLE 1. Characteristics of aluminum-glass facades (own studies)

Type of facade	Description of a construction and its properties
Post and beam facade 	The structure consists of posts and beams. The inner space is filled with glass. From the outside of the facade there are termination bars and masking strips. It is characterized by very high functionality and adaptation in comparison to other aluminum-glass facade systems. It is capable of creating straight, sloping and curb surfaces. Moreover, it has high technical parameters.
Semi-structural facade 	The structure consists of posts and beams corresponding to the post and beam façade systems. From the outside it is smooth and without termination bars and masking strips. Glass is fixed directly to the aluminum construction. The gap between the divisions is filled with a special weather silicone.
Structural facade 	A characteristic feature of the structural façade is the glass-only external surface of the facade, which is obtained by gluing the glass to the aluminum structure. Glass and aluminum are joined using structural silicone. High aesthetics and durability of connections are the advantages of this solution. Its limitation is the inability to use any type of glass for structural bonding, which reduces the functionality of the facade.

Ventilated facades

The second type of common light curtain walls are multilayer claddings. The system that is most frequently used is a ventilated facade. It is a solution based on leaving a ventilation (air) gap between thermal insulation and the decorative element. This procedure allows continuous air flow and, as a result, protects the insulation against moisture. In accordance with ETAG 034 (2010), the ventilated facade can be defined as a set of elements used for enclosing external walls, consisting of the following:

- outer casing (in the form of cement, stone, ceramic, wood, wood-based panels, plastic, metal or laminate) mounted to the grate,
- grate (made of metal or wood), attached to the external walls of the building,
- elements fixing the casing to the grate and the grate to the wall,
- insulation materials (for example, mineral wool, vapour permeable foil).

Ventilated facades have many advantages. They are characterized by high durability, aesthetics, a wide range of decorative claddings that can be used, as well as functionality and the capability to be installed even at low ambient temperatures.

Tender calculation of the lightweight curtain walls

Constructing lightweight curtain walls costs estimating – the market approach with own calculation

The calculation of the tender price of a lightweight curtain wall is a difficult and labour-intensive task for the contractor. What makes the task complicated is the variety of information concerning the

construction, architecture, system, production and assembly, which form the basis for the valuation and calculation of the lightweight curtain wall. All this requires extensive specialist knowledge.

The calculation of the offers of aluminum-glass facades and ventilated facades is usually made as an own calculation which is based on the knowledge and experience of the contractor. However, there exist very few material basics or tools that would simplify the work on the preparation of tender valuations of a light external cladding of the facade. When making calculations, the contractor has to approach each investment individually and carefully analyse the project documentation, including the logistical and organizational considerations. On the one hand, incomplete knowledge or its lack concerning lightweight curtain walls among architects and designers means that the project documentation may contain many shortcomings or inaccuracies. On the other hand, the lack of a specific facade classification system, their parametrization or aluminum metalwork systems prolong the calculation of the facade. The cost estimator, when making a valuation of a lightweight curtain wall, must verify individually whether the assumptions made by the designers are possible not only on the construction site but also in the production plant. The cost estimator who prepares the valuation of a light outer cladding requires specialized and extensive knowledge, as well as experience which, in the case of lightweight curtain walls, will determine the correctness of the calculation, not only from the perspective of estimating costs but also the profit that the contractor would like to achieve.

Constructing lightweight curtain walls costs predicting – the concept of the authors' method

Considering that the estimation of the costs of constructing lightweight curtain walls is based on market approach and own calculation and that this is a complex task which requires extensive specialist knowledge, it seems correct to look for a new method that enables simplification of and acceleration of the process of calculating offer prices by contractors.

Figure 1 presents the authors' method of estimating the tender price for lightweight curtain walls, based on statistical modelling, artificial intelligence and on the conclusions from case studies. The approach proposed allows to estimate the costs of constructing lightweight curtain walls involving the basic data about construction, the type of material used and technological assumptions, within the limits of the expected prediction accuracy.

This paper covers the preparation of the first element necessary to develop the method, that is the identification of factors shaping the tender price of lightweight curtain walls (marked with a thick dashed line in Fig. 1).

Factors shaping the tender price for lightweight curtain walls

Identification of factors

A great number of factors influence the tender price of lightweight curtain walls. The key ones are direct costs including labour, material and equipment. Depending on the type of the facade, an individual skeleton calculation needs

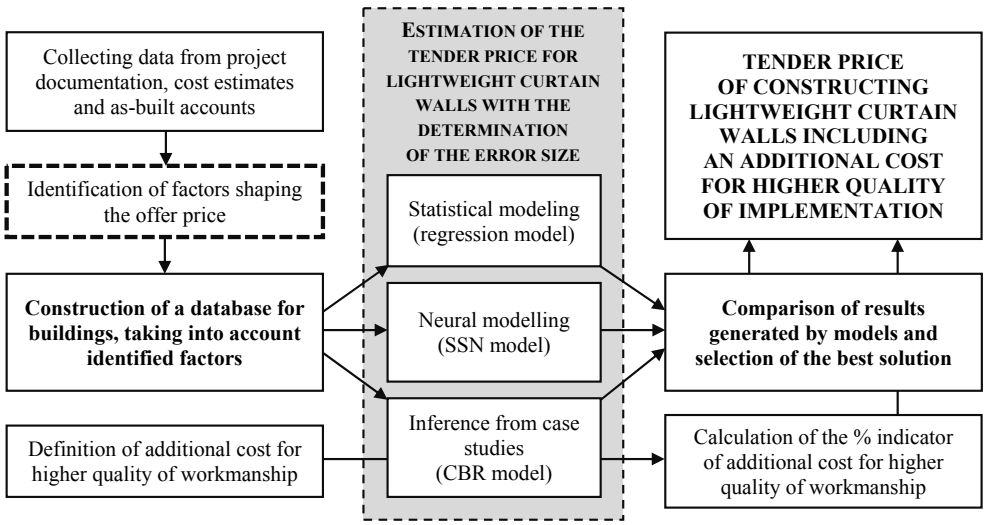


FIGURE 1. Schematic diagram of the construction of the authors' method of estimating the tender price of lightweight curtain walls (own studies)

to be prepared, consisting of aluminum sections offered by the system of aluminum sections for an aluminum facade or an aluminum grate for a ventilated facade. Moreover, the type of filling used for both aluminum and glass facades as well as ventilated facades has a significant impact on the overall facade implementation. Glass, as a material filling the skeleton of the lightweight outer casing construction, greatly affects the cost of the facade. Depending on the technical parameters that the investor wants to get, for a given building the glass panes that will be filled in as glazing units should be appropriately selected. Depending on the type of individual glazing units and their technical characteristics, the price of such a filling changes. For ventilated facades, the largest part of the costs in relation to the whole facade is the type of external cladding used in the form of composite panels, aluminum sheet, quartz sinters or fiber-cement boards.

In the case of facade implementation, one should take into account indirect costs, widely understood, which are closely related to the specific location of the investment, the availability of land around the building or the option of setting scaffolding.

In this paper, the authors attempt to indicate such factors shaping the costs of aluminum-glass facade implementation which affect their size. For this reason a study was performed, including the analysis of design documentation, cost estimate and as-built settlement for cases of facades and ventilated facades in public buildings completed in the years from 2013 to 2018 in central and southern Poland. The authors collected data on 50 cases of implementation of the facades concerned. The research identified 13 factors that were then assigned to 4 groups. The proposed division is illustrated by Table 2.

TABLE 2. A set of factors shaping the tender price of lightweight curtain walls (own studies)

No	Factors and their groups	Designation	Character*
I	General characteristics of the building		
I.1	Location of the building (in the city centre, outside the city centre and the extra-urban area)	X_1	Im
I.2	Function of the building	X_2	Im
II	Characteristics of the size of the building		
II.1	Height of the building	X_3	Me
II.2	Length of the building	X_4	Me
II.3	Width of the building	$X5$	Me
II.4	Number of storeys	X_6	Me
II.5	Occurrence of a patio	X_7	Bin
III	Characteristics of the facade		
III.1	Facade surface	X_8	Me
III.2	Type of aluminum and glass facade	X_9	Im
III.3	Type of the glass used	X_{10}	Im
III.4	Amount and type of ventilated facade	X_{11}	Me
III.5	Number and type of joinery	X_{12}	Me
IV	Implementation quality		
IV.1	Quality of implementation	X_{13}	Me or Bin

*Bin – binary (occurs or not), Me – measurable, Nm – immeasurable.

An analysis of the identified factors

Group I – General characteristics of the building. This group lists basic (general) information about the building in the form of data about its location (X_1) and function (X_2). They have been assigned an immeasurable character. The location contains information about the place of the construction. It has a significant impact on the transport costs of large-size facade elements, such as aluminum sections or glass panes. The authors decided to divide the location factor into three categories: in the city centre, outside the city centre and the extra-urban area. Figures 2 and 3 present the structure of the examined buildings due to their location and function.

As the data presented in Figures 2 and 3 reveal, buildings with glass facades are mostly located in cities (86% of cases) and are most often office buildings (64% of cases).

Group II – Characteristics of the size of the building. This group of factors includes the basic technical parameters of the building, such as height (X_3), length (X_4), width (X_5), or number of storeys (X_6). The nature of these factors is measurable. In addition, in this group a factor was distinguished concerning the occurrence of a patio in the building (X_7 – binary character, that is, either occurring or not). Parameters included in this group not only inform about the elevation area, but also allow the classification

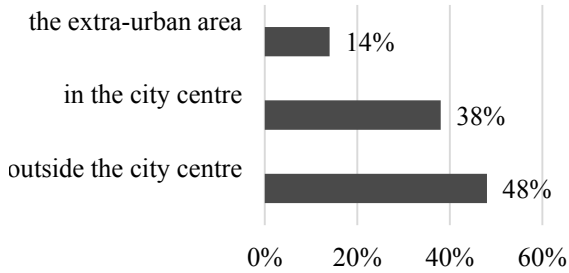


FIGURE 2. Localization of the buildings examined (own studies)

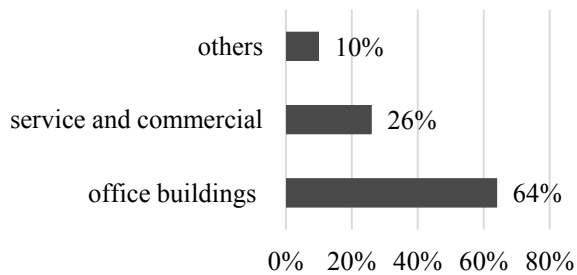


FIGURE 3. Function of the buildings examined (own studies)

of the building according to its height. High-rise buildings generate additional costs due to the use of construction scaffolds and cranes. Moreover, buildings with a patio influence the cost of implementation due to the inability to mechanically transport of the facade elements to the inside of the building and the need to use specialized equipment dedicated to the assembly of glass panes. After the analysis of data collected for 50 buildings, it was found that:

- building height (X_3) is in the range from 6.30 to 50.10 m, the most common range is from 10 to 20 m (50% of the cases studied), with the median value of 15.65 m,
- building length (X_4) is in the range from 10.30 to 148.00 m, the most common length range is from 20 to 60 m (48% of cases), with the median value of 37.38 m,
- building width (X_5) ranges from 7.90 to 76.00 m, the most common width range is from 10 to 30m (40% of cases), with the median value of 25.28 m,
- number of storeys (X_6) ranges from 1 to 14, the most frequent cases are buildings with 2 and 3 floors (11 and 10, respectively, that is 22 and 20% of cases), with the median value of 3.5 floors,
- only in 4 cases (8% of cases), buildings had a patio (X_7).

Group III – Characteristics of the facade. Factors belonging to this group include: facade surface (X_8), type of aluminum and glass facade (X_9), type of the glass used (X_{10}), the amount and type of ventilated facade (X_{11}) and the number

and type of joinery (X_{12}). Factors X_8 and X_9 are not measurable, while factors from X_{10} to X_{12} can be measured. What was significant, in all of the analysed 50 cases it was possible to identify buildings the facades of which were combinations of, for example, types of facade surface (the building had both simple and sloping surfaces), types of aluminum and glass facade (in one part, there was a post and beam facade, in another a semi-structural one, and in yet another, a fire partition wall), or the types of glass (surfaces in m^2, both of fire glass, enamel, as well as composite glass).

As for the factor concerning the type of facade surface (X_8 only 2 examined cases (4% of cases) possessed sloping surfaces occurring in combination with straight surfaces.

The main factor shaping the tender price of the facade is the type of the aluminum-glass facade (X_9). As a result of the conducted research, it was noticed (Fig. 4) that the type of facade most often chosen in design solutions is the post and beam facade (43% of the cases studied). This is probably due to the relatively low cost compared to other facades and its high functionality. The research did not reveal any structural facades (0% of cases). This should be attributed to the high cost of implementation, high labour consumption and the lack of the possibility of using large-sized glass. The approximate effect of a smooth outer surface can be obtained using a semi-structural system. In 34% of studied cases this type of aluminum-glass facade was used. The authors also distinguished a group of fire protection facades. These are facades with the same structure as post and beam or semi-structural ones but additionally with a fire protection contribution to obtain fire resistance. Such facades have been identified in 23% of the cases studied.

A comparison of the costs of individual types of aluminum-glass facades can be found in (Leśniak & Górka, 2018). The costs of making 1 m^2 of aluminum and glass facade in PLN are shown in Figure 5, depending on the facade system used, namely post and beam, structural or semi-structural. In addition, 2 variants of the facade were considered depending on the glazing unit used, that is 6 mm tempered glass + 6 mm float glass + 4 mm safety glass (1st implementation variant) and 8 mm tempered glass + 6 mm float glass + 5 mm safety glass (2nd implementation variant).

Another factor is the type of glass used (X_{10}). The cost of making alumi-

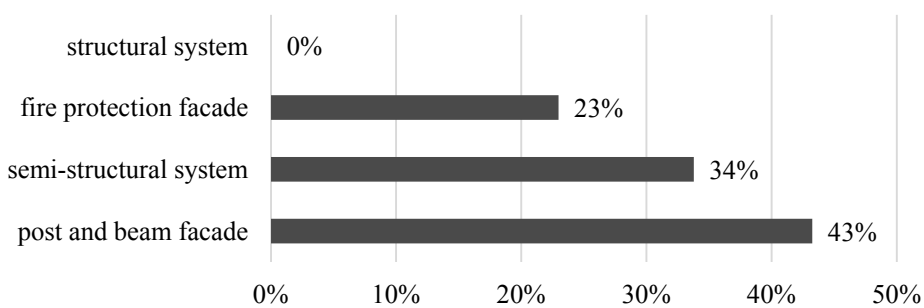


FIGURE 4. Types of aluminum-glass facades used in the analysed cases (own studies)

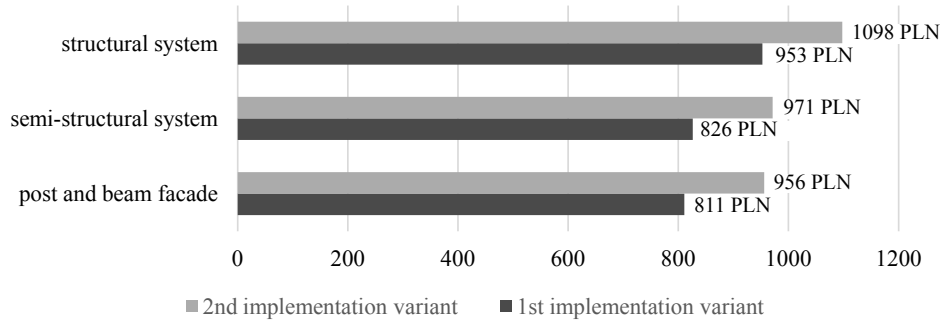


FIGURE 5. The cost of making 1 m^2 of aluminum-glass facade with insulated glass (Leśniak & Górka, 2018)

num-glass facades is primarily influenced by the type of glass used. According to the research, the most common type of filling is a package of insulating glass (69.5% of the examined cases with reference to the facade surface expressed in m^2), while the smallest percentage of use is fire protection glass (1.3%). The results of the analysis are shown in Figure 6.

Facades in lightweight cladding technology are not only aluminum-glass systems, but also ventilated facades. Therefore, a factor describing the quantity and type of the ventilated facade was established (X_{11}) due to the influence of this factor on the cost of implementing the facade. The percentage share of this kind of facades in the analysed buildings is 28% in relation to the facade surface parameter expressed in m^2. The result of the observations is shown in Figure 7.

The last factor identified in group III in the context of the impact on the cost of glass facade implementation is the number and type of joinery used (X_{12}). This factor is measurable and covers the area of windows and doors (in m^2)

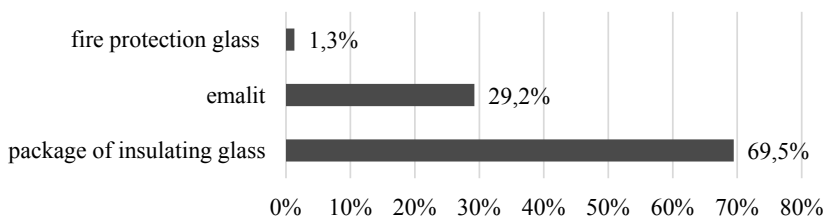


FIGURE 6. Share of particular types of glass in the analysed buildings (own studies)

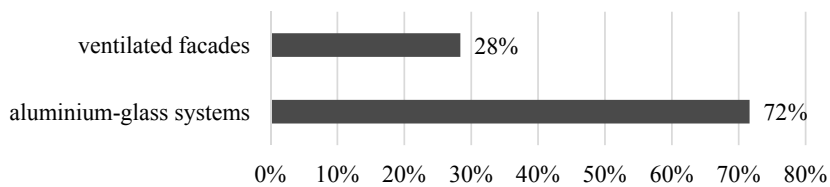


FIGURE 7. The division of facades due to the type of light cladding (own studies)

along with their condition (accessories in units). The amount of door joinery costs is influenced by their type, purpose and the method of assembly. What is noticeable is the trend of gluing the structural glass pane to the window and door frames in order to achieve a uniform facade, without visibly outlined window and door profiles. Moreover, in order for the woodwork to meet the technical requirements and demonstrate high functionality, it must be equipped with appropriate accessories, such as panic fittings, actuators, automatic sliding doors, or access control accessories. All components of such joinery equipment generate additional costs of the comprehensive implementation of the external facades of the building. An example of a set of joinery fittings together with unit costs is presented in Table 3. The table presents the proposed equipment for double-leaf doors which can be taken into consideration for evacuation, aeration and automatic doors used in public buildings where the frequency of opening and closing doors is very large.

TABLE 3. An example of a set of joinery fittings together with unit costs (own studies)

Type of accessory	Doors		
	emergency	aerating	automatic
Panic bar	300.00 PLN	300.00 PLN	–
Aerating (fresh air) system	–	4000.00 PLN	–
Electric strikes	300.00 PLN	300.00 PLN	–
Closer to RKZ	1 500.00 PLN	1 500.00 PLN	–
Steel bar	200.00 PLN	200.00 PLN	–
Automatic door system	–	–	5 500.00 PLN

Group IV – Implementation quality. The low quality of facade elements causes the final effect to reduce the aesthetics of the building. To avoid this, the quality of the facade must be ensured. With the assurance of the quality of work there are expenditures that the construction company incurs to control, test, audit or train appropriately teams performing works and supervising the execution. Therefore, the authors decided to specify the factor related to the quality of implementation (X_{13}) which refers to the costs of quality assurance for lightweight curtain walls. The nature of this factor is twofold because: (1) part of the checks and tests performed during structural bonding or audits conducted by external units as part of, for example, checking compliance with the ISO 9001 standard, as well as HST tests (thermal curing tests of tempered glass, that is "Heat Soak Tests"), which are additionally performed for tempered glass in order to obtain a very high probability that the glass will not break up spontaneously, are optional (binary character of the factor, namely occurring or not), and (2) guarantees given by contractors are expressed in months or years (the measurable nature of the factor). During the analysis of 50 buildings, it was found that:

– quality tests of structural bonding were conducted in 6 cases (in all ca-

ses where structural gluing of glass was recorded),
– HST tests were performed in 22 cases (44% of cases),
– duration of the guarantee period ranges from 2 to 10 years, the most common length of the guarantee is 5 years (66% of cases).

Conclusions

Lightweight curtain walls constitute the present and future of public buildings. They are characterized by lightness of form, originality and aesthetic finishing. The ease of shaping non-linear surfaces means that designers can create objects which do not have to be based solely on a rectangular plan. Estimating the costs of lightweight curtain walls in practice is based on a market approach and own calculation which requires extensive and specialist knowledge. The authors made an attempt to find a new method of facilitating and accelerating the process of calculation of tender prices by contractors. In the first stage, they identified 13 factors affecting the costs of implementing a given type of facade, categorizing them subjectively into 4 groups. The collected database of 50 cases allowed to indicate that buildings with glass facades for the most part are located in urban agglomerations outside the strict city centre and are most often office buildings. The types of glazing and joinery used are the factor that produces the highest costs. In further research work, the authors plan to build a method for estimating the costs of lightweight curtain walls based on identified factors.

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Summary

Identification of factors shaping tender prices for lightweight curtain walls. A reliable estimation of the tender prices for lightweight curtain walls is a complex and time-consuming process for the contractor, as it depends on many factors related to both the technical parameters of the designed façade and the investor's requirements for the solutions selected. The aim of the paper is to identify the factors affecting the costs of manufacturing lightweight curtain walls. Data regarding the complexity of curtain wall construction costs was obtained on the basis of the analysis of project documentation, cost estimates and as-built accounts for selected 50 public buildings. The authors identified the factors affecting the costs of aluminum-glass facades and ventilated facades. Their identification is the first element necessary to develop a new method of predicting the costs of implementation of such types of facade which are included in the authors' research plans.

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