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Research paper

Pre-design cost modeling of facade systems using the GAM method

A. Leśniak[1], M. Górka[2]

Abstract: The cost estimation at the pre-project stage provides an important decision-making indicator for the future of the project. With a preliminary cost estimation, project participants can make financial decisions and cost control. The aim of this paper is to propose a model for estimating the costs of facade systems before the pre-design stage, using the GAM (Generalized Additive Model) method. The commonly used method for the valuation of facade systems is based on individual calculation. Such valuation process is complicated and time consuming. For this reason the search for a new forecasting method is justified. The database developed for modelling purposes includes 61 cases of real costs of system façade execution for public buildings. Each case is described by 16 parameters (namely, input variables). The average absolute percentage error (MAPE) was used to assess the model, which takes the value of 14,26% for the generalized model with a logarithmic binding function and 11.77% for the model with an identity binding function. On the basis of the studies and the results obtained, it can be concluded that the constructed model is useful and can improve the process of forecasting system façade costs at the pre-projection stage.

Keywords: facade systems for public buildings, cost estimates, Generalized Additive Models (GAM)

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[1] Prof., DSc., PhD., Eng., Cracow University of Technology, Faculty of Civil Engineering, Institute, 24 Warszawska street, 31-155 Cracow, Poland, e-mail: agnieszka.lesniak@pk.edu.pl, ORCID: https://orcid.org/0000-0002-4811-5574

[2] MSc., Eng., Cracow University of Technology, Faculty of Civil Engineering, Institute, 24 Warszawska street, 31-155 Cracow, Poland, e-mail: monika.gorka@pk.edu.pl, ORCID: https://orcid.org/0000-0002-5985-2078

1. Introduction

A construction project is a combination of interdependent activities aimed at satisfying the construction needs of the investor or the owner of the building. Therefore, it is not only the preparation and construction of a building object in a specific place and time, but also its preparation and extension, superstructure, renovation or demolition [11], [12]. The erection and operation of a building is usually associated with a burden on the environment, therefore modern construction must be accompanied by the idea of sustainable development and the resulting environmentally friendly attitudes [21]. Emphasis is put on the choice of building materials [15], energy efficiency of buildings in urban areas [35] and the methods of the construction and demolition waste minimisation [13]. Execution of a construction project in the planned time, with the assumed quality and costs is a determinant of success of both the investor and the contractor. These three parameters of a construction project are a frequent subject of publication. The search for new methods of schedule optimization was discussed, for example, in works of [5], [14], [27] presented a newly developed model used to smooth out schedules in terms of maintaining crew work continuity. In terms of planning over time, many of the current works concern the identification of causes and modelling of construction delays [20], [28]. It is indicated that the effects of the delay in construction contract execution are always negative for each party involved [2], thus the identification of methods that reduce delays are a major research problem. Recent publications on quality in construction projects mainly concern the identification and evaluation of Factors Affecting Quality [26], noticed that the main factors influencing the quality of execution of construction projects are mainly unqualified and incompetent contractors, and the lack of involvement of the supervisory team. In terms of costs, the researchers propose to use mathematical methods to build models to speed up the cost calculation process, such as the regression method [24], support vector regression [8] artificial neural networks [19] artificial neural network systems [9] Case-based reasoning method [21]. The search for methods to support cost forecasting does not only concern the construction phase [25] proposed a model allowing for the accurate assessment of the costs of renovation and repair works on a building at a given stage of its use, while [37] discussed an original model for estimating the whole life cost of a building which allows the quantification of the increase in costs resulting from the incurred and assessed risk. Aspects of risk in construction projects, as well as methods of its identification and assessment can be found in such works as [18], [34].

For both the investor and the contractor, estimating the costs of implementation is an important element of planning each construction project. Very often, already in the pre-design phase, the participants of the project take actions aimed at estimating the costs of construction works planned to be performed. Early estimation of the costs of works makes it possible to make a decision on the implementation of the project and to plan the budget. The basis for cost forecasting is the analysis of the project, conceptual and the accuracy of graphic and descriptive elaborations influences the degree of detail of cost calculations at the stage preceding the basic design works. It is acceptable that in the future these costs may change due to the adoption of other detailed design solutions, improvement of the quality of workmanship, or unpredictable conditions which the contractor may encounter at the construction site.

The present paper addresses the problem of calculating the costs of the execution of façade systems used in public facilities. Aluminium and glass façades are a type of elevation which are inseparable from public utility buildings and constitute the mainstay of urban architecture [6]. Since the calculation of costs of facade systems and ventilated facades is a complicated and time-consuming task [16], the authors have attempted to build a pre-design cost forecasting model of facade systems. Such cost forecasting models in the construction industry are usually created using regression or artificial intelligence methods [8, 9, 19, 24]. No attempt has been made so far to build a cost forecast model using the GAM (Generalized Additive Model) method. This method allows to take into account both linear and non-linear influence of factors on the research problem, without showing any previously assumed relationships between them [7]. The use of GAM allows to determine the error pattern for different databases, which results in a better quality of matching the model with real data. The task of the generalised add-on model is to maximise the quality of predictions of the Y-dependent variable from various distributions through non-parametric independent variable functions. To the model under development uses a database containing values of factors (independent variables), as identified by the authors, influencing the costs of facade systems (dependent variable) and the actual costs of their implementation.

2. Problems in calculating the cost of facade systems

The elevation is a part of the building's image, its aesthetics, form and architectural body. Aluminium and glass facades, forming the external walls of public buildings, are a component of modern urban architecture, shaping public space and internal harmony of the city. One of the most common types of lightweight curtain walls are aluminium and glass facades made of aluminium and glass sections. The second popular solution is multilayer cladding, among which ventilated facades are most often chosen. Both solutions are described in greater detail in [17]. The basic and dominant component of direct costs of facade construction is the cost of materials. As it was shown in [16], in the case of aluminium and glass facades, it is mainly the costs of aluminium sections, forming the frame of the structure, and glass filling the space between the structures. It is the type of glazing used in the unit and its technical characteristics that determine the price of the filling. In the case of ventilated facades, built in the form of an aluminium grate filled with mineral wool with the external cladding added, the cost of materials is generated primarily by the type of cladding used. In the case of construction works related to the execution of facades, great attention is paid to widely understood indirect costs, which are related to the location of the investment, availability of land around the building, or the possibility of setting up building scaffolding and cranes.

Cost calculations for the implementation of facade systems are carried out in the form of individual calculations. The degree of complexity of the valuation is influenced by constructional, architectural and system data, parameters connected with production, assembly technology, transport processes and the need to use specialized construction equipment. The cost assessment also concerns the process and possibility of realization of design assumptions in the pro-educational plant. The necessity of individual approach to each realization makes the cost calculation process very time consuming. A more detailed description of this process can be found in the work by [16].

In an earlier publication, [17] , the authors identified the factors influencing the costs of facade systems implementation. As a result of their research, 4 groups of factors were identified: group I comprising basic (general) information about the building; group II comprising basic technical parameters of the building, group III comprising factors describing the characteristics of the facade and group IV concerning the quality of workmanship. The factors indicated will be used in the construction of the present cost forecast model as input variables.

3. Calculation of implementation costs of facade systems using additive models

3.1. Additive models – general characteristics

Generalised GAM additive models are based on the assumption that the values of the transformed dependent variable are predicted according to a linear combination of independent variables. Such a transformation can be obtained by means of a binding function as a non-parametric function obtained by smoothing out the graph of partial residuals. Different binding functions [22] can be used in GAM models. The simplest and most popular binding functions are: identical, logarithmic and power function. The general linear model for the dependent variable takes the following form [1], [7]:

$$Y = g(b_0 + b_1X_1 + b_2X_2 + \ldots + b_kX_k) + e \tag{1.1}$$

where:
g – is a function,
e – is an error
Y – expected values of the dependent variable,
$X_1 \ldots X_k$ – represent k values of predictive variables
b_0, $b_1 \ldots b_k$ – regression coefficients estimated by multiple regression.

The reverse function to function g is function $f(m_iY)$, called the binding function [1], [7]:

$$f(m_iY) = b_0 + b_1X_1 + b_2X_2 + \ldots + b_kX_k \tag{1.2}$$

where:
m_iY – means the expected value of Y.

Therefore, the GAM method is very effective in various fields of science, for example, in the construction industry, it was used by the author of the publication to forecast the time of construction processes [30], to forecast the actual concrete mix consumption [29], or to forecast apartment prices [31]. The GAM method was also used in meteorology [3], chemistry [36] and economics [4]. Generalised additive models are mainly used to maximise the quality of the prediction of the dependent variable Y through the functions of the explanatory variables that are associated with the dependent variable by combining functions.

The paper proposes the use of the method of generalized additive models due to the heterogeneity of the data obtained during quantitative and qualitative studies, and also due to the data distribution other than normal.

3.2. Data used in the model

When building a model of predicting the costs of facade systems in the form of aluminium-glass facades and ventilated facades, 16 factors identified in previous works by the authors were enumerated [17]. These are general characteristics, technical parameters and factors influencing the cost calculation of facade systems. Input variables are presented in Table 1. The database consists of 61 cases, namely public buildings.

Table 1. Factors shaping the costs of facade construction

No.	Factors	Designatio*n*	Value
1.	Function of the building	X_1	Office building. Service and commercial building
2.	Total area	X_2	m^2
3.	Height of the building	X_3	m
4.	Shape of the building	X_4	Rectangle Polygon
5.	Level of complexity	X_5	Low Medium High
6.	Posst and beam facade	X_6	Not occurs – 0 Occurs – 1
7.	Semi-structural facade	X_7	Not occurs – 0 Occurs –1
8.	Fire protection facade	X_8	Not occurs – 0 Occurs –1
9.	Ventilated facade – composite panels	X_9	% in relations to the entire analyzed area
10.	Ventilated facade – fiber cement board	X_{10}	% in relations to the entire analyzed area
11.	Glass – emalit	X_{11}	% in relations to the entire analyzed area
12.	Single-chamber combined glass	X_{12}	% in relations to the entire analyzed area
13.	Double-chamber combined glass	X_{13}	% in relations to the entire analyzed area
14.	Doors	X_{14}	% in relations to the entire analyzed area
15.	Windows	X_{15}	% in relations to the entire analyzed area
16.	Location of the building	X_{16}	In the city centre. Oustside the city centre. Extra-urban area

Using the method of classification and regression trees (C&RT), the significance of the influence of individual factors on the dependent variable, that is, the cost of facade systems, was examined. The data are presented in Figure 1. The greatest influence is shown by the predictor which is the total area, followed by the function of facility, glass enamel, height of the facility and level of complexity. The smallest influence is shown by the factor: shape of the building.

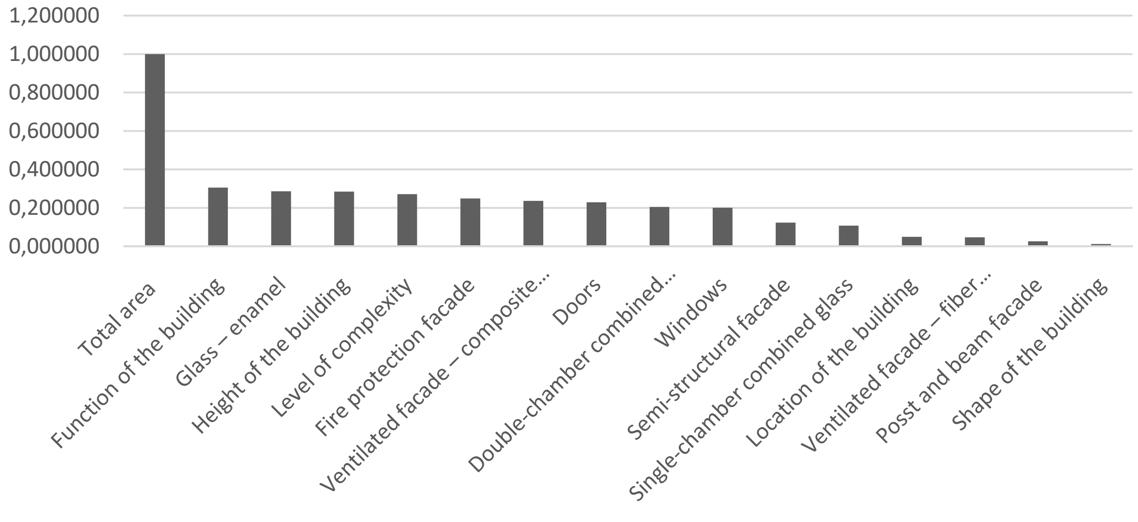

Fig 1. Validity of independent variables

In the course of the calculations performed, multi-factor models require the specification of the distribution of the variables. Then, one should determine whether the variables have a normal distribution. Therefore, a thesis was put forward about the normal distribution of variables. The Shapiro-Wilk test was used for calculations, forming a null hypothesis H_0 that the variables have a near-normal distribution, and an alternative hypothesis H_1: ~ H_0, that the variable does not have a distribution close to normal. The hypothesis was verified at the significance level $\alpha = 0{,}05$. For 61 cases, the critical value was $W_\alpha = 0{,}954$ [1]. The calculated statistical values W of the Shapiro-Wilk test are presented in Table 2. For variables of a qualitative nature, a pseudo-fuzzy scaling in the range <0,1–0,9> was made, while the binary variables are coded 1 when they occur, and 0 when they do not, respectively.

Table 2. Statistical value W of the Shapiro-Wilk test

No.	Factors	$W_{0,05}$ $n = 61$	W – calculated	Normal distribution
1.	Cost of constructing facade systems (Y)	0.954	0.81087	NO
2.	Function of the building	0.954	0.61988	NO
3.	Total area	0.954	0.79506	NO
4.	Height of the building	0.954	0.84628	NO
5.	Shape of the building	0.954	0.22435	NO
6.	Level of complexity	0.954	0.66873	NO
7.	Post and beam facade	0.954	0.61425	NO
8.	Semi-structural facade	0.954	0.63180	NO
9.	Fire protection facade	0.954	0.56115	NO
10.	Ventilated facade – composite panels	0.954	0.60129	NO
11.	Ventilated facade – fiber cement board	0.954	0.22181	NO
12.	Glass – enamel	0.954	0.75170	NO
13.	Single-chamber combined glass	0.954	0.41143	NO
14.	Double-chamber combined glass	0.954	0.86705	NO
15.	Doors	0.954	0.55218	NO
16.	Windows	0.954	0.62727	NO
17.	Location of the building	0.954	0.76114	NO

Figure 2 and Figure 3 show two selected cases of variable normality analysis for the independent variable with the highest significance, total area.

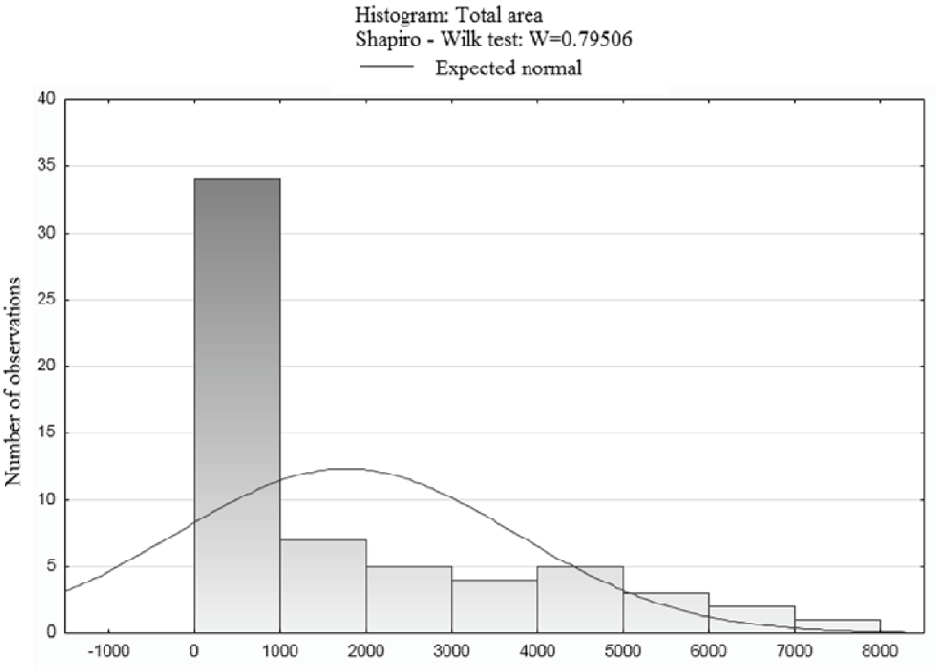

Fig 2. Histogram of independent variable distributions: total area

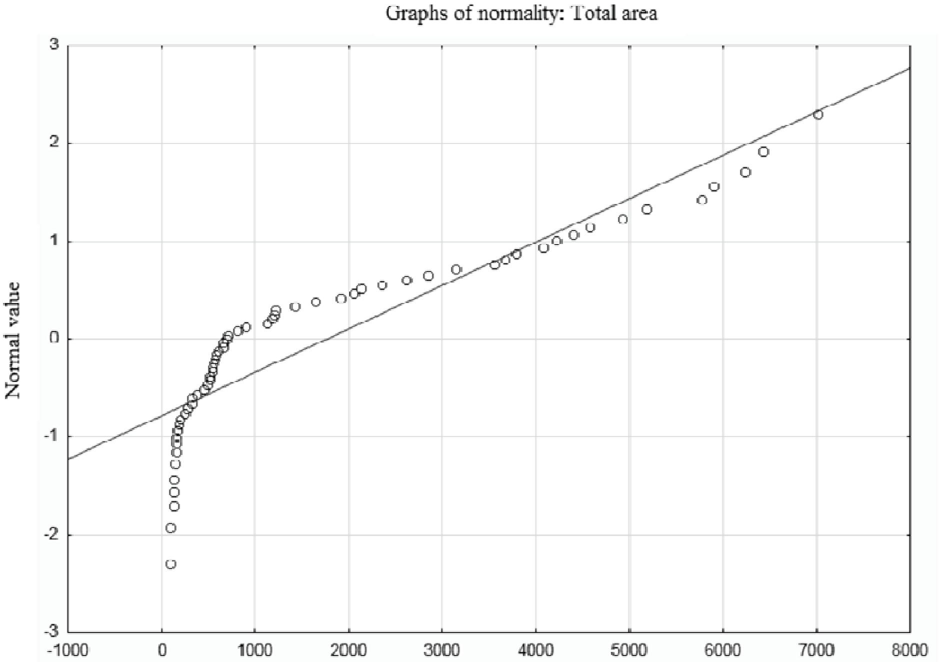

Fig 3. Graphs of normality of independent variable distributions: total area.

On the basis of the calculations received, the thesis on the normality of variable distributions should be rejected.

3.3. Presentation of the models and results obtained

Based on the database, an additive model was built using the STATISTCA software. Due to the rejection of the thesis about the normal distribution of variables for calculations, it was assumed that the distribution of the forecast variable is gamma. The logarithmic function was chosen as the binding function. Table 3 presents a summary of the fit of the GAM model for the gamma distribution and the logarithmic binding function.

Table 3. Summary of GAM model fit; Gamma distribution, logarithmic binding function

Algorithm summary: Obseved: *Y* – Costs of facade systems Gamma distribution; Binding function: logarithmic						
	Final deviation	Residuals – df	Number of observations	External iterations	Scale assessment	R^2 *100%
Value	1.940510	13.00041	61	13	0.149265	97.65820

The determination factor R^2 for the GAM model with gamma distribution and logarithmic binding function is 0.976582, which means that the combination of independent variables ($X_1 ... X_{16}$) explains the dependent variable *Y*, the cost of facade systems, in 97.6582%.

Figure 4 and Figure 5 show a graphical analysis of the generalized additive model residues that were generated using the STATISTICA program. It allows to check whether the assumption about normal distribution of residuals is correct and whether the dispersion of data along the regression line is uniform.

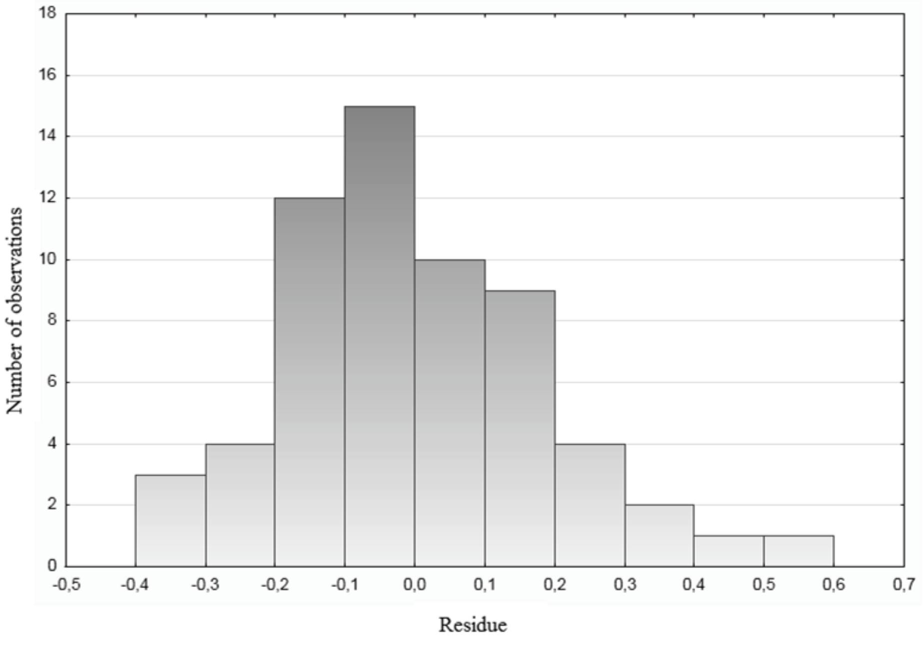

Fig 4. Residual histogram

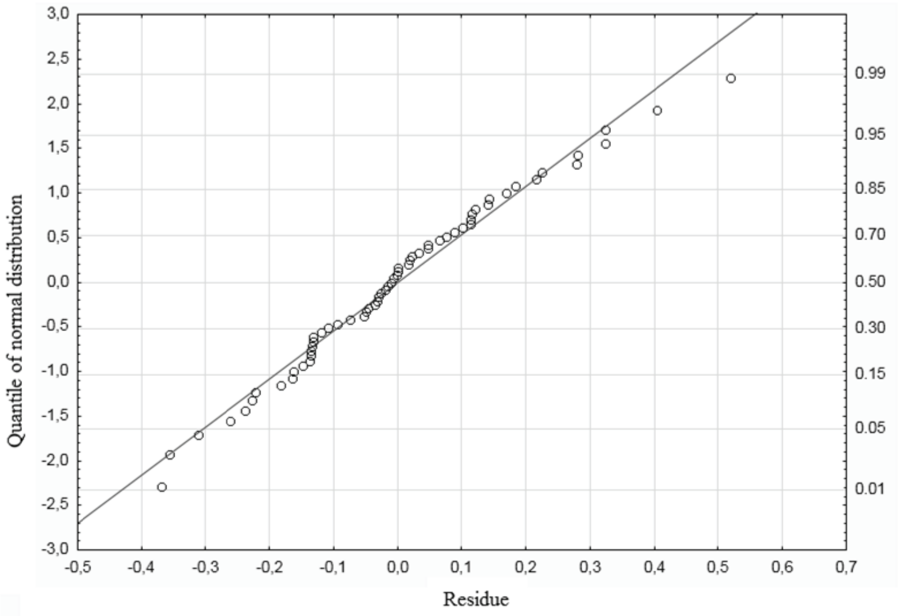

Fig 5. Residual normality

The second model under analysis is a generalized additive model with gamma distribution and an identical binding function. Table 4 summarises the fit of the GAM model.

Table 4. Summary of the GAM model fit; Gamma distribution, identity binding function

Algorithm summary: Observed: *Y* – Facade system costs Gamma distribution; Binding function: Identity						
	Final deviation	Residuals - df	Number of observations	External iterations	Scale assessment	R^2 *100%
Value	1.967030	13.04280	61	17	0.150814	97.62619

The determination coefficient R^2 for this model is at a very similar level and amounts to 0.9762619. Figure 6 presents the residual histogram and Figure 7 residual normality to examine the assumption about the normality of residual distribution and uniformity of residual dispersion along the regression line.

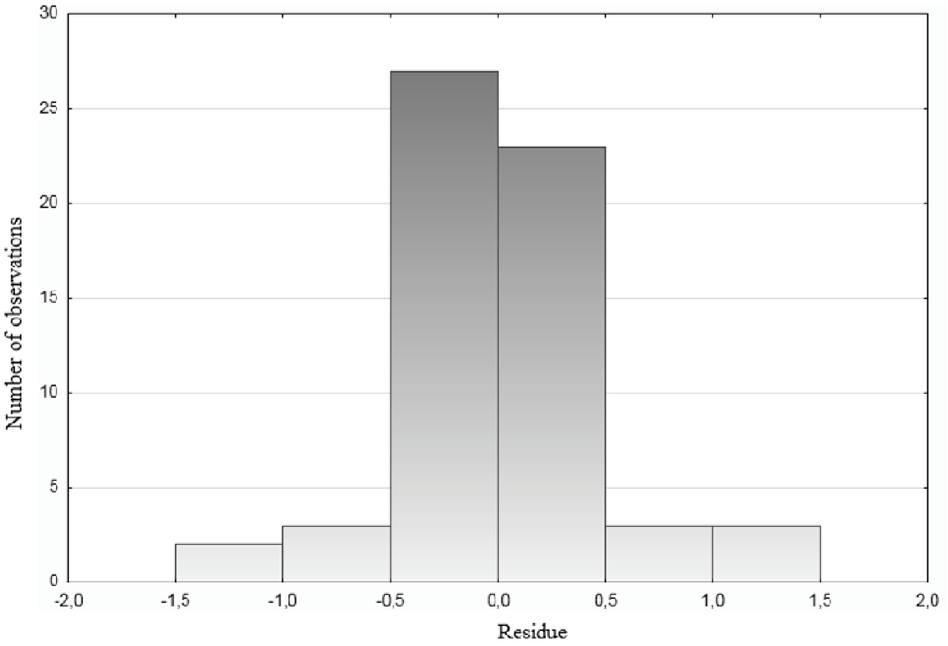

Fig 6. Residual histogram

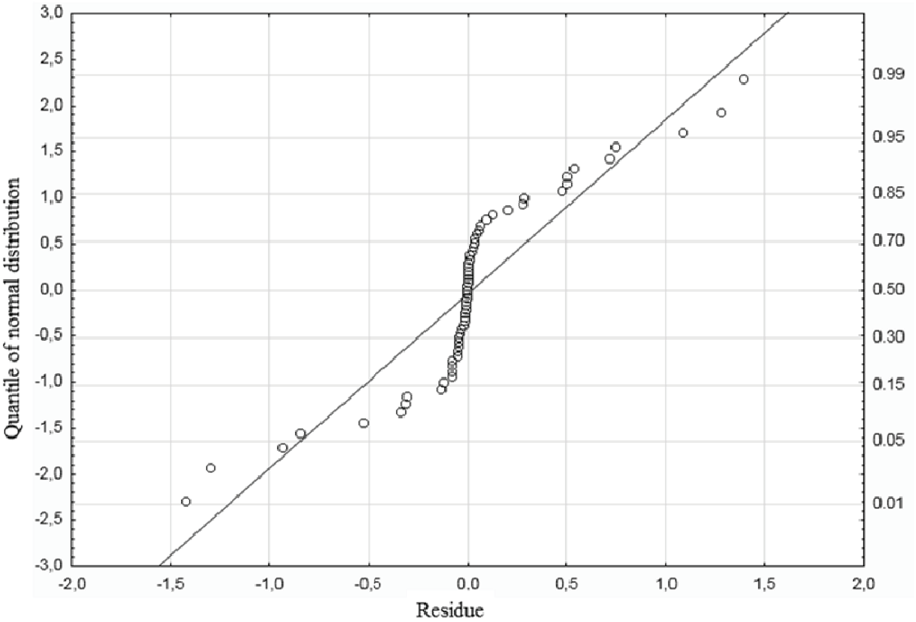

Fig 7. Residual normality

Analyzing the distribution and normality of residuals for the two models, it can be concluded that for the GAM model with the logarithmic function, the variance of the residue component shows greater uniformity.

3.4. Comparison of models and discussion

In order to examine the goodness of fit of the models, and above all to assess the correctness of the prediction, MAE and MAPE forecast errors were calculated using the following formulas.

$$MAE = \frac{1}{T-n} \sum_{i=T-n}^{T} \left| Y_i - Y_{ip} \right| \tag{1.3}$$

$$MAPE = \frac{1}{T-n} \sum_{i=T-n}^{T} \frac{\left| Y_i - Y_{ip} \right|}{Y_i} \tag{1.4}$$

where:

MAE – average error achieved

MAPE – average absolute percentage error

T – the sum of the number of calculation and forecast periods

n – number of forecast periods

Y_i – actual value of the variable in period i

Y_{ip} – projected value of the variable in period i

The results obtained are presented in Table 5.

Table 5. Forecast errors for generalized additive models

Designation	Characteristic	
	GAM: Gamma distribution; logarithmic function	GAM: Gamma distribution; identity function
Coefficient of determination R^2	0.9765	0.9762
MAE error	0.2539	0.2543
MAPE %	14.2677	11.7755

The MAPE forecast error for the generalized model with a logarithmic binding function is 14.2677%, while for the model with an identity binding function is 11.7755%. Both results indicate that the model is correct and that the additive model with gamma distribution and identity binding function shows better fit.

5. Conclusions

In the present paper, the authors attempted to build models supporting the prediction of estimation of the cost of facade systems in the form of aluminium and glass facades and ventilated facades. 61 cases of public buildings were analyzed, both office and commercial buildings. Based on the collected data from project, cost and implementation documentation, factors affecting implementation costs were determined. The developed base with quantitative and qualitative data was used to build generalized additive models as a tool for cost estimation of facade systems.

Analyzing the classification and regression trees, the significance of the effects of individual predictors was examined, and then the distribution of individual dependent and independent variables was assessed based on the Shapiro-Wilk test. The thesis about the normality of distribution was rejected. Therefore, for further calculations, generalized additive models with gamma distribution and, respectively, logarithmic and identity binding functions were used.

The developed cost forecast models are characterized by a very high R^2 determination coefficient of 0.9765 for the GAM model with logarithmic function, and 0,9762 for the GAM model with the identity function. The MAPE forecast error was 14.2777% and 11.7755%, respectively, and MAE 0.2539 and 0.2543, respectively. These error values are acceptable when estimating costs at the pre-design stage. Instead, better quality prediction should be sought, for instance, by increasing the number of cases. Based on the results obtained, it can be concluded that the constructed model is useful and can improve the process of forecasting the costs of system facades at the pre-design stage.

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Przedprojektowe modelowanie kosztów systemów elewacyjnych z wykorzystaniem modeli GAM

Słowa kluczowe: systemy elewacyjne budynków użyteczności publicznej, oszacowanie kosztów, modele addytywne

Streszczenie:

Prawidłowe realizowanie danego przedsięwzięcia budowlanego to połączenie wielu współzależnych działań, którego celem jest zaspokojenie potrzeb budowlanych zarówno inwestora jak i użytkownika obiektu budowlanego. Należy nie tylko zwracać uwagę na materiał użyty do budowy, nadbudowy czy remontu budynku zgodny z ideą zrównoważonego budownictwa, ale także na metodę i sposób realizacji. Każda realizacja powinna być dokładnie zaplanowana w czasie, przy założonym koszcie i jakości. Dlatego te trzy parametry są częstym tematem publikacji. Poszukiwane są metody optymalizacji harmonogramów oraz kosztów przedsięwzięcia budowlanego, wykorzystujące narzędzia matematyczne, jak regresja, sztuczne sieci neuronowe, wnioskowanie z przypadku, dodatkowo szacowane jest ryzyko poszczególnych etapów procesu budowlanego, aby zminimalizować niepewność i poziom niepowodzenia inwestycji. Prawidłowe i zrównoważone połączenie wszystkich aspektów decyduje o sukcesie inwestora oraz wykonawcy.

Zarówno dla inwestora jak i wykonawcy oszacowanie kosztów realizacji jest istotnym elementem planowania każdego przedsięwzięcia budowlanego. Bardzo często już w fazie przedprojektowej uczestnicy przedsięwzięcia podejmują działania zmierzające do oszacowania kosztów planowanych do wykonania robót budowlanych. Wczesne oszacowania kosztów robót umożliwia podjęcie decyzji o realizacji przedsięwzięcia i zaplanowanie budżetu. Podstawą prognozy kosztów jest analiza projektu, koncepcyjnego a dokładność opracowań graficznych i opisowych wpływa na stopień szczegółowości kalkulacji kosztowych na etapie poprzedzającym podstawowe prace projektowe. Dopuszczalne jest, że w przyszłości koszty te mogą ulec zmianie z powodu przyjęcia innych szczegółowych rozwiązań projektowych, podniesienia jakości wykonania, czy nieprzewidywalnych warunków, które wykonawca może napotkać na budowie.

W publikacji podjęto problem kalkulacji kosztów wykonania systemów elewacyjnych stosowanych w obiektach użyteczności publicznej. Wykonanie kalkulacji kosztów realizacji systemów fasadowych oraz elewacji wentylowanych jest zadaniem skomplikowanym i czasochłonnym. Autorzy podjęli próbę prognozowania kosztów realizacji systemów elewacyjnych z wykorzystaniem metody uogólnionych modeli addytywnych. Zadaniem uogólnionego modelu addytywnego jest maksymalizacja jakości przewidywań zmiennej zależnej Y z różnych dystrybucji, poprzez nieparametryczne funkcje zmiennych niezależnych. Do budowy modelu wykorzystano opracowaną bazę danych zawierającą wartości zidentyfikowanych przez autorów czynników (zmiennych niezależnych) wpływających na kształtowanie się kosztów wykonania systemów elewacyjnych (zmiennej zależnej).

Podstawowym i dominującym składnikiem kosztów bezpośrednich wykonania fasad elewacyjnych jest koszt materiałów. W przypadku fasad aluminiowo-szklanych stanowią go głównie koszt kształtowników aluminiowych, tworzących szkielet konstrukcji oraz szkło wypełniające przestrzeń pomiędzy konstrukcją. W przypadku elewacji wentylowanych, zbudowanych w formie rusztu aluminiowego wypełnionego wełną mineralną z dołożoną okładziną zewnętrzną koszt materiałów generuje przede wszystkim rodzaj zastosowanej okładziny. W przypadku robót budowlanych związanych z wykonaniem fasad dużą uwagę przywiązuje się do szeroko pojętych kosztów pośrednich, które są powiązane z lokalizacją inwestycji, dostępnością terenu wokół budynku.

Sporządzenie kalkulacji kosztów realizacji systemów fasadowych odbywa się formie kalkulacji indywidualnej. Na stopień skomplikowania wyceny wpływ mają dane konstrukcyjne, architektoniczne, systemowe, parametry związane z produkcją, technologia montażu, procesów transportowe i konieczność zastosowania specjalistycznego sprzętu budowlanego. Wycena kosztów dotyczy także procesu i możliwości realizacji założeń projektowych w zakładzie produkcyjnym. Konieczność indywidualnego podejścia do każdej realizacji sprawia, że proces kalkulacji kosztów jest bardzo czasochłonny.

W celu budowy modelu predykcji kosztów wykonania systemów elewacyjnych w postaci: fasad aluminiowo-szklanych i elewacji wentylowanych zaproponowano 16 czynników, takich jak: funkcja budynku, powierzchnia całkowita, wysokość i kształt obiektu, jego lokalizacja, poziom skomplikowania elewacji, rodzaj zastosowanego systemu fasady aluminiowo szklanej, rodzaj zastosowanego szkła oraz rodzaj elewacji wentylowanej. Są to cechy ogólne, parametry techniczne oraz czynniki mające wpływ na kalkulację kosztów systemów elewacyjnych. Baza danych składa się z 61 przypadków (obiektów użyteczności publicznej).

Wykorzystując metodę drzew klasyfikacyjnych i regresyjnych (C&RT) zbadano istotność wpływu poszczególnych czynników na zmienną zależną, czyli koszt wykonania systemów elewacyjnych. Zgodnie z otrzymanymi wynikami, największy wpływ wykazują predyktory jakimi są powierzchnia całkowita, kolejno rodzaj obiektu, szkło emalit, wysokość obiektu, poziom skomplikowania. Najmniejszy wpływ wykazuje czynnik – bryła budynku. Dodatkowo została postawiona teza o normalności rozkładów zmiennych. Wykorzystano do obliczeń test Shapiro-Wilka, formułując hipotezę zerową H_0, że zmienne posiadają rozkład zbliżony do normalnego, oraz hipotezę alternatywną H_1: $\sim H_0$, że zmienna nie posiada rozkładu zbliżonego do normalnego. Zweryfikowano hipotezę na poziomie istotności $\alpha = 0{,}05$. Na podstawie otrzymanych obliczeń należy odrzucić tezę o normalności rozkładów zmiennych.

Ze względu na odrzucenie tezy o normalności rozkładu zmiennych do obliczeń i budowy uogólnionego modelu addytywnego przyjęto, że rozkład zmiennej prognozowanej jest gamma. Jako funkcje wiążącą wybrano funkcję logarytmiczną. Uzyskano wyniki, gdzie współczynnik determinacji R^2 wynosi 0,976582, co oznacza, że kombinacja zmiennych niezależnych ($X_1 \ldots X_{16}$) wyjaśnia zmienną zależną Y – koszt systemów elewacyjnych aż w 97,6582%.

Drugi model poddany analizie to uogólniony model addytywny z rozkładem Gamma i funkcją wiążącą identycznościową. Dla tego modelu współczynnik determinacji R2, kształtuje się na bardzo podobnym poziomie i wynosi 0,9762619. Analizując wykresy rozkładu reszt oraz normalność reszt dla dwóch modeli, można wnioskować, że dla modelu GAM z funkcją logarytmiczną wariancja składnika reszt wykazuje większą jednorodność. Autorzy dodatkowo obliczyli błąd prognozy MAE oraz MAPE. Błąd prognozy MAPE kształtował się odpowiednio na poziomie 14,26% i 11,77%, a MAE odpowiednio 0,2539 i 0,2543. Otrzymane błędy są akceptowalne przy szacowaniu kosztów na etapie przedprojektowym. Natomiast należy dążyć do lepszej jakości predykcji, np. poprzez zwiększenie liczby przypadków.

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