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Influence of structural system on the construction time and cost of residential projects

Authors:

Boris Dimitrijević, PhD. CE
ZOP Inženjering d.o.o., Serbia
boris.dimitrijevic@yahoo.com

Assoc.Prof. **Zoran Stojadinović**, PhD.
University of Belgrade
Faculty of Civil Engineering
jokazs@eunet.rs

Assist.Prof. **Dejan Marinković**, PhD. CE
University of Belgrade
Faculty of Civil Engineering
dejan@grf.rs

Mirjana Dimitrijević, MSc. CE
ZOP Inženjering d.o.o., Serbia
miradebeljak@yahoo.com

Subject review

Boris Dimitrijević, Zoran Stojadinović, Dejan Marinković, Mirjana Dimitrijević

Influence of structural system on the construction time and cost of residential projects

The aim of the research is to investigate the ways in which various structural systems and time influence the cost of construction of RC structures of residential buildings, and to identify and quantify key parameters that are of highest significance in this respect. The data taken from the database of completed projects are analysed using the leave-one-out-cross-validation and regression analysis. Limit numerical values confirmed by the redesign of two structures from the database are identified as key parameters. These values define in quantitative terms the rationality of the design solution and the rationality of construction work scheduling. They can also be used in practice in order to optimise the cost and time of construction work on residential buildings.

Key words:
residential buildings, structural system, costs, duration, key parameters

Pregledni rad

Boris Dimitrijević, Zoran Stojadinović, Dejan Marinković, Mirjana Dimitrijević

Utjecaj konstrukcijskog sustava na troškove i trajanje građenja stambenih objekata

Cilj istraživanja je ispitivanje utjecaja vrste konstrukcijskog sustava i trajanje na troškove građenja AB konstrukcije stambenih objekata, kao i identifikacija i kvantifikacija ključnih parametara koji na to najviše utječu. Podaci iz baze dovršenih projekata ocijenjeni su primjenom jednostrukog unakrsnog ocjenjivanja i regresijske analize. Za ključne parametre identificirane su granične numeričke vrijednosti koje su potvrđene preprojektiranjem dvaju objekata iz baze. Te vrijednosti na kvantificiran način definiraju racionalnost projektantskog rješenja kao i racionalnost planiranja organizacije građenja. Mogu se primijeniti i u praksi s ciljem racionaliziranja troškova i trajanja građenja stambenih objekata.

Ključne riječi:
stambeni objekti, konstrukcijski sustav, troškovi, trajanje, ključni parametri

Übersichtsarbeit

Boris Dimitrijević, Zoran Stojadinović, Dejan Marinković, Mirjana Dimitrijević

Auswirkungen des Konstruktionssystems auf die Kosten und die Dauer des Baus von Wohngebäuden

Das Ziel der Untersuchung ist die Überprüfung der Auswirkungen der Art des Konstruktionssystems und die Dauer auf die Baukosten von Stahlbetonkonstruktionen von Wohngebäuden, wie auch die Identifizierung und Quantifizierung von Schlüsselparametern, die sich am häufigsten darauf auswirken. Die Daten aus der Datenbank fertiggestellter Projekte wurden anhand einer Kreuzbewertung und Regressionsanalyse beurteilt. Für die Schlüsselparameter wurden nummerische Grenzwerte identifiziert, die durch die Umplanung zweier Objekte aus der Datenbank bestätigt wurden. Diese Werte definieren auf quantifizierende Art und Weise die Rationalität der Projektlösung, wie auch die Rationalität der Planung der Bauorganisation. Diese können auch in der Praxis angewendet werden, um die Kosten und die Dauer des Baus von Wohngebäuden zu rationalisieren.

Schlüsselwörter:
Wohngebäude, Konstruktionssystem, Kosten, Dauer, Schlüsselparameter

1. Introduction

In construction industry, the reduction of unnecessary construction costs and durations is of utmost significance for the success of both clients and contractors. From the standpoint of clients, this reduction increases profit and favours faster capital turnover. From the point of view of contractors, such practice leads to cost reduction and increase in profit margins, while also contributing to competitive advantages of companies.

The realisation of superstructure construction works is highly significant, as it greatly influences total construction costs and the rate at which all other types of work are realised. This is the very reason why superstructure works have to be realised at such rate to enable minimisation of the overall duration and cutting down costs to reasonable levels, while having in mind technology and quality requirements. The objective of this research is to analyse the ways in which various superstructure types influence the cost and duration of construction work on residential projects.

The superstructure of a building is the system composed of the load-bearing and non-load-bearing elements, whose role is to ensure the strength, stability and resistance of a building. Massive, skeleton, and mixed structural systems [1] are analysed in the scope of this study. In the case of massive systems, the vertical part of the reinforced-concrete structure is formed of massive walls. In skeleton systems, the vertical part of the RC structure is formed of columns, while it is formed of walls and columns in the case of mixed systems [1]. Depending on the position of walls, massive systems can be transverse, longitudinal, or combined [1].

The objective of the paper is to analyse influence of superstructure types on the duration and cost of construction of RC structures, and to identify and quantify key parameters that are of highest significance in this respect. Limit numerical values, capable of determining in practical and quantitative terms the rationality of design solutions, and the rationality of construction work planning, will be identified as key parameters. By the use of such key parameters, it becomes possible to improve design and scheduling procedures, reduce costs, and increase efficiency in the realisation of construction works. This research is the continuation, further elaboration, and extension of the research conducted in the scope of doctoral thesis of the lead author of this paper [2].

2. Methodology

The proposed research methodology is composed of the steps:

1. Database establishment and analysis
   - database establishment for purposes of the research,
   - identification and quantification of parameters that influence on the cost and duration of construction works for a RC building,
   - analysis, systemisation and selection of key parameters,
2. Analysis of information contained in database
   - regression analysis,
   - leave-one-out cross validation (LOOCV)
3. Testing – case study
4. Practical implementation of research results

Individual steps of the proposed methodology are analysed in full detail in the following sections.

The research was conducted using the performance based design (PBD) principles. Such an approach implies the use of tools and methods through which the results from already realised projects are used at the design stage, so that construction of new structures would bring the desired effects and fulfilment of planned objectives [3]. In this case, performance criteria are the cost and duration of construction work, and the objective of the research is to define numerical performance values to be achieved at the design stage, and subsequently realised at the construction stage.

Although performance based design principles are used in many areas all over the world, just a few authors have actually dealt with the issue of using the PBD in relation to the cost and duration of construction work [4]. In early phases of projects, costs are most frequently estimated based on regression analysis [5, 6], neural networks [6], and case based reasoning [7, 8]. The PBD is mostly used on construction projects for acheiving technical requirements for high-rise buildings [9], in the analysis of earthquake and hurricane effects [10-13], fire protection measures [14] and energy efficiency [15], and in the design of bridges [16], embankments [17], etc. In addition, the research relating to the cost and duration of construction work can not be conducted easily due to lack of good quality databases, i.e. due to inexistence of objective and comparable data from completed projects. For these reasons, it is indispensable to conduct the study of completed projects and to form a list of key parameters that can be used in formulating design criteria, the objective being to design optimum superstructures of residential buildings, both in regard of cost and duration of construction work [18].

3. Database

3.1. Establishment of database for research purposes

The database consists of 28 residential buildings ranging in height from 5 to 9 floors above ground, with the total gross areas of 2,360 to 10,800 sq.m., and with the typical floor gross area ranging from 390 to 1350 sq.m. When selecting buildings, a special attention was paid to the comparability of data so as to enable determination of the influence of a particular superstructure types on the cost and duration of construction work. For that reason, buildings were selected as follows: all buildings were built in the same city (Belgrade), the works were carried out by a single company using its own manpower, formwork produced by a single manufacturer was used (Peri [19]), the required level of quality was the same for all buildings, construction duration was relatively short (2011 to 2017), unit rates for resources were comparable, and the analysis involved floors above ground only. Construction of basement levels depends on a number of local conditions (geotechnical features, foundation pit protection, financing modalities, etc.) that are of variable nature, and can greatly influence the cost and schedule. That is why basement levels they were not included in this research.

Table 1. Database with information measured on completed projects

Objekt	Površina bruto [m²]	Broj etaža	Vrsta konstrukcije	Materijal							Oplata	Kran	Rad			Troškovi proizvodnje konstrukcije [€/m²]	Proizvodna cijena konstrukcije troškovi poslovanja 15% [€/m²]	Tržišna cijena konstrukcije profit 10% [€/m²]	Tržišna cijena zidanja [€/m²]	Ukupna tržišna cijena GG gradova [€/m²]	Trajanje [dan/etaža]
				Beton			Armatura			Ukupno materijal [€/m²]	Ukupno oplata [€/m²]	Ukupno kran [€/m²]	Rad		Ukupno rad [€/m²]						
				utrošak [m³/m²]	cijena [€/m³]	ukupno [€/m²]	utrošak [kg/m²]	cijena [€/m²]	ukupno [€/m²]				utrošak [h/m²]	cijena [€/h]							
1	2.603.62	7	mixed	0.3	63.36	19.01	37.04		20.37	39.38	8.27	6.45	3.79		19.71	73.81	84.88	93.37	18.37	111.74	8.86
2	4.730.54	8	mixed	0.29	63.24	18.34	33.66		18.51	36.85	7.37	4.06	3.84		19.97	68.25	78.49	86.34	16.26	102.6	9.38
3	7.912.70	9	mixed	0.28	63.25	17.71	37.38		20.56	38.27	7.66	2.83	3.48		18.1	66.86	76.88	84.57	17.47	102.04	10.22
4	9.115.00	9	mixed	0.28	62.75	17.57	36.21		19.92	37.49	7.19	2.42	3.44		17.89	64.98	74.73	82.2	18.65	100.85	10
5	7.456.72	9	mixed	0.28	63.24	17.71	38.08		20.94	38.65	6.67	2.83	3.47		18.04	66.2	76.12	83.74	18.54	102.28	9.44
6	7.484.40	9	mixed	0.29	63.15	18.31	38.11		20.96	39.27	7.03	2.87	3.7		19.24	68.41	78.68	86.54	17.37	103.91	9.67
7	10.796.63	9	mixed	0.28	62.95	17.63	30.53		16.79	34.42	6.87	2.02	3.51		18.25	61.56	70.79	77.87	18.49	96.36	9.89
8	4.810.50	8	mixed	0.29	63.26	18.35	34.39		18.91	37.26	7.89	4.00	3.61		18.77	67.92	78.11	85.92	17.05	102.97	9.38
9	3.324.00	7	mixed	0.32	63.24	20.24	37.45		20.60	40.83	8.36	5.56	3.87		20.12	74.88	86.11	94.72	16.82	111.54	10.14
10	2.676.00	7	mixed	0.31	63.38	19.65	38.71		21.29	40.94	8.74	6.9	3.57		18.56	75.14	86.41	95.06	17.93	112.99	10.14
11	8.607.33	8	masivni poprečni	0.32	63.88	20.44	41.61		22.89	43.33	8.12	2.43	3.89		20.23	74.11	85.22	93.74	16.29	110.03	10.5
12	6.423.53	7	masivni poprečni	0.31	63.25	19.61	42.48		23.36	42.97	8.72	2.88	4.21		21.89	76.46	87.93	96.73	15.56	112.29	10.14
13	6.280.30	7	masivni poprečni	0.33	63.49	20.95	41.93		23.06	44.01	8.38	2.94	4.13		21.48	76.81	88.33	97.16	15.71	112.87	10.14
14	5.964.70	8	skeletni	0.25	62.76	15.69	34.91		19.20	34.89	60.2	3.04	3.07		15.96	59.91	68.9	75.79	20.93	96.72	8.25
15	6.027.81	8	skeletni	0.26	62.84	16.34	37.10	0.55	20.41	36.74	6.12	3.34	3.12	5.20	16.22	62.43	71.79	78.97	20.56	99.53	8.63
16	6.050.89	8	skeletni	0.26	62.84	16.34	37.77		20.77	37.11	5.9	3.42	2.98		15.5	61.93	71.22	78.34	20.49	98.83	8
17	3.946.54	6	skeletni	0.25	62.84	15.66	37.31		20.52	36.18	7.56	4.02	3.08		16.02	63.78	73.34	80.68	23.39	104.07	6.86
18	3.806.00	7	skeletni	0.26	62.64	16.3	38.52		21.19	37.48	7.67	3.82	3.21		16.69	65.66	75.51	83.07	23.22	106.29	7.14
19	2.379.00	5	skeletni	0.27	62.97	17.00	31.51		17.33	34.33	6.52	4.78	3		15.6	61.23	70.42	77.46	20.36	97.82	6.6
20	2.508.00	5	skeletni	0.28	63.11	17.67	31.63		17.40	35.07	6.61	4.76	3.11		16.17	62.61	72	79.2	20.28	99.48	7.2
21	2.924.50	5	skeletni	0.26	62.52	16.26	30.46		16.75	33.01	6.16	4.02	2.82		14.66	57.85	66.53	73.18	22.48	95.66	7
22	2.474.00	5	skeletni	0.28	63.17	17.69	30.83		16.96	34.64	6.68	4.75	2.98		15.5	61.57	70.81	77.89	22.14	100.03	7
23	2.363.00	5	skeletni	0.27	62.86	16.97	31.22		17.17	34.14	7.14	4.97	3.13		16.28	62.53	71.91	79.1	20.04	99.14	7
24	5.530.00	8	masivni oba pravca	0.35	65.68	22.99	39.76		21.87	44.86	9.96	3.98	5.45		28.34	87.14	100.21	110.23	10.56	120.79	11.25
25	3.379.00	6	masivni oba pravca	0.38	65.5	24.89	40.44		22.24	47.13	11.15	5.19	5.49		28.55	92.02	105.82	116.41	12.25	128.66	11
26	4.912.00	8	masivni oba pravca	0.37	65.49	24.23	40.11		22.06	46.29	9.96	4.37	5.14		26.73	87.35	100.45	110.5	14.07	124.57	10.88
27	5.250.96	8	masivni oba pravca	0.36	65.9	23.72	47.14		25.93	49.65	9.49	4.2	5.75		29.9	93.24	107.23	117.95	8.79	126.74	11.28
28	4.832.32	8	masivni oba pravca	0.37	65.46	24.22	44.62		24.54	48.76	9.23	4.48	5.84		30.37	92.84	106.77	117.44	8.63	126.07	11

An extract from the database is shown in Table 1, and the following data are given for each building: type of superstructure system, resources used, unit price of resource, direct production costs, production and market price of the structure, market price of masonry work, market price of rough construction work, and average duration of typical floors per building. Direct production costs for a superstructure are calculated as a sum of the products of measured consumptions of chosen parameters and their unit prices. The production price of the superstructure is the sum of direct and indirect company operating costs (15 % of direct costs). The market price of the superstructure is obtained by increasing the production price for company profit amounting to 10 % [2].

3.2. Identification and quantification of parameters influencing duration and cost of constructing a RC structure

The cost and duration needed to build a reinforced-concrete structure are directly dependent on the material, equipment, machinery, labour, and their unit prices. The materials that dominantly influence the cost of a structure are concrete and reinforcement. Unit rates of concrete differ in buildings, and are calculated based on unit rates and according to proportion of individual types of concrete in the total quantity of concrete. For example, the self-compacting concrete with the unit rate of c_1 and proportion u_1 is used for concreting vertical RC elements, while an ordinary pumped concrete with the unit rate of c_2 and proportion u_2 is used for horizontal RC elements. This information is used to calculate an average unit rate of concrete used in an entire structure, based on the following equation:

$$c = c_1 \cdot u_1 + c_2 \cdot u_2 \tag{1}$$

In the case of machinery, the machinery for vertical transport and the machinery for concrete works can be differentiated. The cost of machinery for concrete works is included in the unit price of concrete, while a tower crane is used for vertical transport of formwork and other materials. To enable comparison of data and to avoid influence of various construction site conditions, the database covers only those buildings/structures that are characterized by similar length of transport of fresh concrete (up to 5 km), i.e. by the same price of external transport, and where the internal transport is carried out in the same way (mobile concrete pumps).

Thus the following resources were singled out as parameters whose influence on the cost and duration of construction work for a RC building will be tested: concrete, reinforcement, formwork, crane, and labour [2]. To enable comparison of data and universality of application, the consumption of these resources is presented in square meters of gross area of a building/structure. When testing real influence of superstructures on construction costs, it is necessary to take into account the fact that various superstructure systems require different quantities of material for masonry works, i.e. for the construction of residential units. For that reason, the market price of rough construction works per gross area of a building is selected as the main parameter for estimating the cost of a superstructure system. The comparability of various superstructure systems was thus ensured [2]. In this research, rough construction works denote works relating to the RC structure and masonry.

The time needed for building a typical floor depends on the quantity of works, i.e. on the total number of required working hours, as well as on the number of workers needed for this activity. In order to provide for a situation in which work conditions, i.e. intensity of work, will be the same on all structures, approximately the same average work space (about 25 sq.m.) was defined per one worker. In this way, conditions were created to consider duration of work on a floor primarily as a function of the superstructure system selected.

The influence of masonry works on the duration of work was not considered as these works are normally organised so as to follow the pace of construction of the superstructure, and differing quantities of masonry works at various superstructure systems were solved by an optimum selection of the number of workers.

3.3. Analysis, systemisation and selection of key parameters

In Table 1, buildings are classified and grouped according to the type of superstructure system, and a correlation is made between the parameters selected and the duration and cost of construction work. The market price of rough construction works ranges from 95.66 to 128.66 €/m², and an average time needed to build a typical floor ranges from 6.60 to 11.28 days per floor.

Average market prices for the superstructure, masonry work

Table 2. Average market price of superstructure and rough construction works, and average duration for building a typical floor

Vrsta konstrukcije	Tržišna vrijednost konstrukcije (struktura cijene)					Tržišna vrijednost zidanja [€/m²]	Tržišna vrijednost GG gradova [€/m²]	Trajanje [dan/etaža]
	Materijal [€/m²]	Oplata [€/m²]	Kran [€/m²]	Rad [€/m²]	Ukupno [€/m²]			
Skeletni	44.73	8.4	5.18	20.06	78.37	21.39	99.76	7.37
Mješoviti	48.5	9.62	5.05	23.86	87.03	17.7	104.73	9.71
Masivni poprečni	54.95	10.63	3.48	26.82	95.88	15.85	111.73	10.26
Masivni oba pravca	59.88	12.6	5.62	36.4	114.5	10.86	125.36	11.08

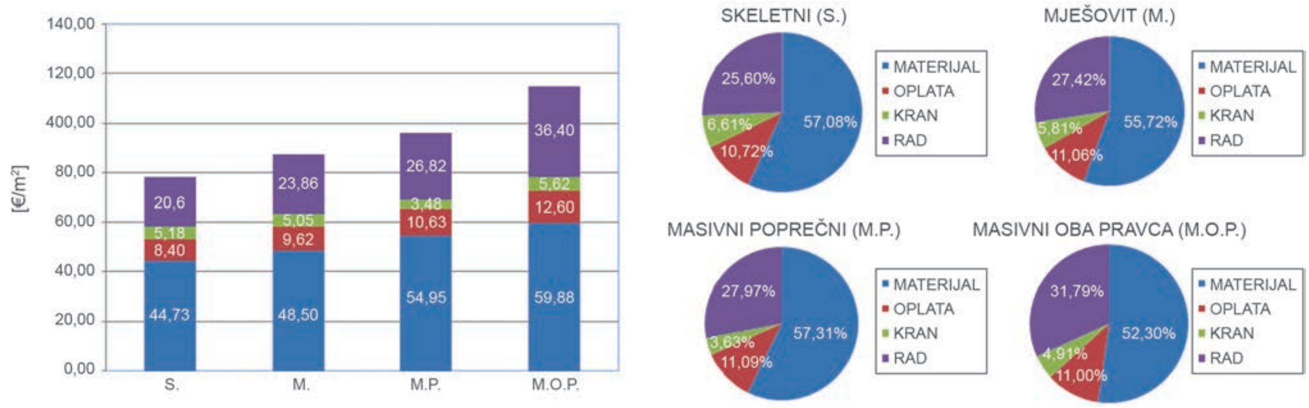

Figure 1. Breakdown of market price of superstructure works for various superstructure systems

and rough construction work (GG works), and an average duration for building a typical floor, are also defined (Table 2).

The market price of the superstructure is the lowest in case of a skeleton structural system, while it is the highest in case of a massive system in both directions (Table 2). The price of materials, equipment, and work also increases from skeleton system to massive system, but with a different intensity (Figure 1).

Diagrams presented in Figure 1 show that the formwork and crane hold a constant share in the total price of the superstructure (approximately 15 %), while the share of material and labor is very significant and amounts to approximately 85 % of the total cost of the structure. That is why the concrete, reinforcement, and labor are considered to be key parameters that decisively influence the cost of superstructures. Average consumption of key parameters per square meter of gross area of buildings increases from skeleton system to massive system (Table 3).

Table 3. Average consumption of key parameters per type of RC structure

Vrsta konstrukcije	Prosječni utoršci ključnih parametara		
	Beton [m³/m²]	Armatura [kg/m²]	Rad [h/m²]
Skeletni	0.26	34.13	3.05
Mješoviti	0.29	36.16	3.63
Masivni poprečni	0.32	42.01	4.08
Masivni oba pravca	0.37	42.41	5.53

The quantity of work is the greatest in case of the massive system with walls in both direction (Figure 1), which is why the longest duration is needed to build a typical floor. The total market price of rough construction works, and the market price of superstructure, are the lowest in case of a skeleton system and the price increases for the mixed system and massive system while, at the same time, the market price of masonry decreases (Figure 2)

Compared to skeleton superstructure system, rough construction works are more expensive on all other systems: on the mixed system by 4.98 %, on the massive transverse system by 12 %, and on the massive system in both directions by 25.66 %. Compared to skeleton system, the realisation of a typical floor lasts longer in other superstructure systems: mixed system by 31.75 %, massive transverse system by 39.21 %, and massive system in both directions by 50.34 %.

This proves that the choice of a superstructure system greatly affects the cost and duration of construction work on residential projects for the studied data set (buildings).

4. Validation of database information

The data contained in the database were validated in order to determine their significance. The validation was made using the regression analysis and the leave-one-out-cross-validation. The significance check was conducted for two parameters: total

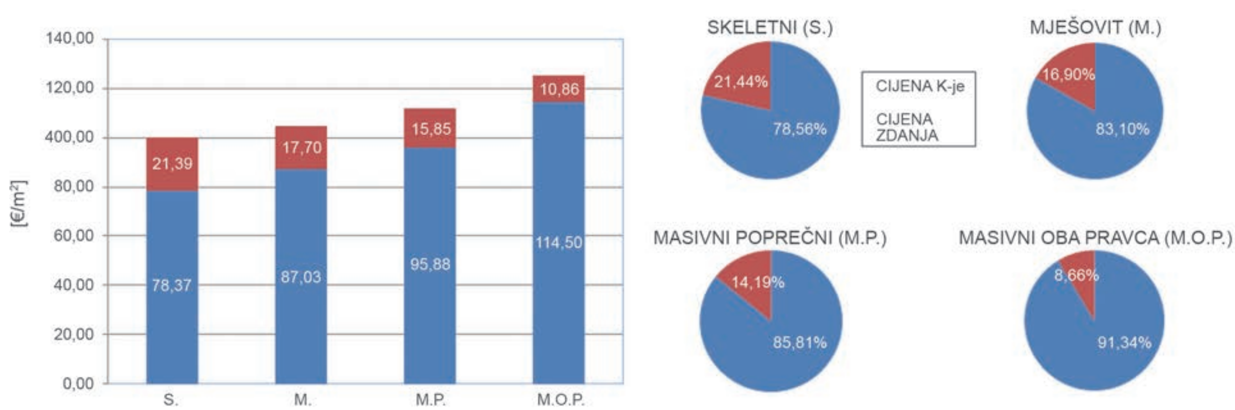

Figure 2. Breakdown of market price of rough construction works for various superstructure systems

market price of rough construction works and the duration for constructing a typical floor, which both depend on the consumption of key parameters [2]. These parameters were selected as they enable correct comparison of various superstructure systems.

4.1 Regression analysis

The regression analysis is used to check the dependence between various occurrences, the objective being to estimate the value of a dependent variable based on one or more independent variables. The regression analysis implies logical definition of the cause-and-effect relationship between the occurrences [20]. In this study, the cause is the change of superstructure type which is quantified through quantities of key parameters (concrete, reinforcement, labour), and the effect is the change in price and duration of construction [2].
As the quantity of data contained in the database is small, a simple regression with no less than 12 pairs of data can be used in the analysis [20]. In order to ensure proper preconditions for the use of single regression, the independent variable must be shown as a mixed measure of three key parameters: quantity of concrete U_B (m^3/m^2), quantity of reinforcement U_A (kg/m^2) and quantity of work U_R (h/m^2). As different units are used for the above parameters, their normalised values were calculated as follows [7]:

$$Ui,norm = \bar{U}i = \begin{cases} \dfrac{(Ui - Ui,min)}{(Ui,max - Ui,min)} & \forall Ui,max > Ui,min \\ 0,50 & \forall Ui,max = Ui,min \end{cases} \quad (2)$$

Normalised values and weight coefficients were used to define key parameters [21] and superstructure factor $F_{k,i}$ [2]:

$$F_{K,i}(\,\%) = W_B \bar{U}_{B,i} + W_A \bar{U}_{A,i} + W_R \bar{U}_{R,i} \quad (3)$$

where individual terms stand for:

$\bar{U}_{B,i}$, $\bar{U}_{A,i}$ i $\bar{U}_{R,i}$ - normalised quantities of concrete, reinforcement, and labor

W_B, W_A i W_R - weight coefficients for the consumption of concrete, reinforcement, and labor.

All three key parameters (concrete, reinforcement and labor) are equally important, and so weight coefficients are also equal: $W_B = W_A = W_R = 33$ %. The calculation of the superstructure factor for all 28 buildings is shown in Table 4.
Two simple regression models are shown in the paper. In both cases, superstructure factor of $F_{K,i}$(%) was adopted for the independent variable X, while the dependent variable Y is presented as the price of construction C, (€/m^2), i.e. as construction duration T_i (day/floor) [2]. Data pairs for regression models are shown in Table 4.
Table 4 served as the basis for forming scatter plots for the price of rough construction works and for the duration of construction of a typical floor (Figure 3). Scatter plots show that the regression curve for the price of construction exhibits an approximately linear dependence when related to superstructure factor (Figure 3), while the regression curve for the duration of construction of a typical floor assumes an approximately logarithmic form (Figure 3).
Regression curves for the price and duration of construction, with standard regression errors and coefficient of determination R^2, are represented by equations (4) and (5):

$$C = 93{,}95 + 0{,}3697 \cdot F_K, \quad St = 2{,}65\ (€/m^2), \quad R^2 = 0{,}933 \quad (4)$$
$$T = 3{,}9935 + 1{,}5692 \cdot \ln(F_K),\ St = 0{,}79\ (dan/etaža),\ R^2 = 0{,}7429 \quad (5)$$

High values of coefficients of determination show that a significant part of variability of dependent variables (93,3 % and 74.29 %, for price and duration of construction, respectively) can be explained by superstructure factor as an independent variable. This demonstrates that the quality of both modes is satisfactory, but also that the regression model for price has a greater accuracy in the prediction of dependent variable.
To justify the use of regression model for predicting a dependant variable, it was necessary to test the significance of regression relationship, i.e. to test whether the explaining variable is significant for the behaviour of the dependent variable [22]. Model significance testing was conducted using the F test

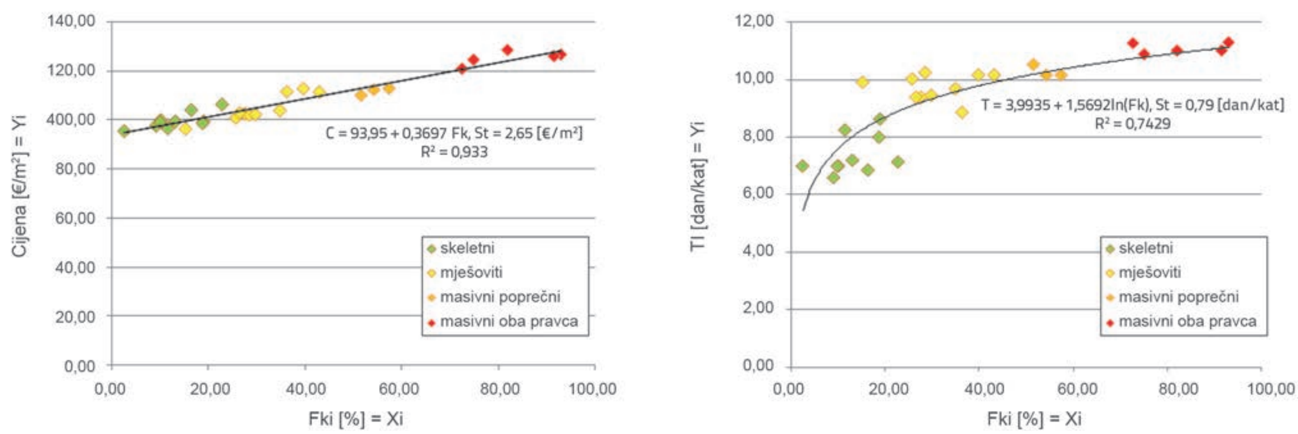

Figure 3. Scatter plots and regression curves for price and duration of construction

Table 4. Calculation of the superstructure factor and input data for the regression model

Objekt	Vrsta konstrukcije	Podaci za proračun faktora konstrukcije						Parovi podataka		
		Beton	Armatura	Rad	Beton	Armatura	Rad	Faktor konstrukcije Xi=Fki [%]	Ukupna tržišna cijena Yi=Ci [€/m^2]	Trajanje izrade k-Je Yi=Ti [dan/etaža]
		utrošak [m^3/m^2]	utrošak [kg/m^2]	utrošak [h/m^2]	nor.utr. [%]	nor.utr. [%]	nor.utr. [%]			
1	mješoviti	0.3	37.04	3.79	38.46	39.45	32.12	36.31	111.74	8.86
2	mješoviti	0.29	33.66	3.84	30.77	19.18	33.77	27.63	102.6	9.38
3	mješoviti	0.28	37.38	3.48	23.08	41.49	21.85	28.52	102.04	10.22
4	mješoviti	0.28	36.21	3.44	23.08	34.47	20.53	25.77	100.85	10
5	mješoviti	0.28	38.08	3.47	23.08	45.68	21.52	29.79	102.28	9044
6	mješoviti	0.29	38.11	3.7	30.77	45.86	29.14	34.9	103.91	9.67
7	mješoviti	0.28	30.53	3.51	23.08	0.42	22.85	15.29	96.36	9.98
8	mješoviti	0.32	34.39	3.61	30.77	23.56	26.16	26.56	102.97	9.38
9	mješoviti	0.31	37.45	3.87	53.85	41.91	34.77	43.07	111.54	10.14
10	mješoviti	0.32	38.71	3.57	46.15	49.91	24.83	39.75	112.99	10.14
11	masivni poprečni	0.31	41.61	3.89	53.85	66.85	35.43	51.52	110.03	10.5
12	masivni poprečni	0.33	42.48	4.21	46.15	72.06	46.03	54.2	112.29	10.14
13	masivni poprečni	0.25	41.93	4.13	61.54	68.76	43.38	57.31	112.87	10.14
14	skeletni	0.26	34.91	3.07	0	26.68	8.28	11.54	96.72	8.25
15	skeletni	0.26	37.1	3.12	7.69	39.81	9.93	18.95	99.53	8.63
16	skeletni	0.25	37.77	2.98	7.69	43.82	5.3	18.75	98.83	8
17	skeletni	0.26	37.31	3.08	0	41.07	8.61	16.39	104.07	6.86
18	skeletni	0.27	38.52	3.21	7.69	48.32	12.91	22.75	106.29	7.14
19	skeletni	0.28	31.51	3	15.38	6.29	5.96	9.12	97.82	6.6
20	skeletni	0.26	31.63	3.11	23.08	7.01	9.6	13.1	99.48	7.2
21	skeletni	0.28	30.46	2.82	7.69	0	0	2.54	95.66	7
22	skeletni	0.27	30.83	2.98	23.08	2.22	5.3	10.1	100.03	7
23	skeletni	0.27	31.22	3.13	15.38	4.56	10.26	9.97	99.14	7
24	masivni oba pravca	0.35	39.76	5.45	76.92	55.76	87.09	72.52	120.79	11.25
25	masivni oba pravca	0.38	40.44	5.49	100	59.83	88.41	81.92	128.66	11
26	masivni oba pravca	0.37	40.11	5.14	92.31	57.85	76.82	74.9	124.57	10.88
27	masivni oba pravca	0.36	47.14	5.75	84.62	100	97.02	92.94	126.74	11.28
28	masivni oba pravca	0.37	44.62	5.84	92.31	84.89	100	91.48	126.07	11

Table 5. F-test for regression models relating to price and duration of construction

F test - regresijski model za cijenu građenja grubih građevinskih radova					
Izvor	**Br. stupnjeva slobode**	**Zbroj kvadrata**	**Srednji kvadrat**	**F**	**P > F**
Model	1	2544.712	2544.712	362.155	< 0.00001
Pogreška	26	182.691	7.027		
Ukupno	27	2727.403			
F test - regresijski model za trajanje izrade konstrukcije					
Model	1	47.045	47.045	75.137	< 0.00001
Pogreška	26	1.279	0.626		
Ukupno	27	63.324			

(Table 5). If the value F is greater than Fkr the zero hypothesis is rejected and an alternative hypothesis is accepted, i.e. the coefficient for independent variable does not equal zero in regression equation.

The value $Fkr_{(1;26;0,01)}$= 7.72 is obtained from F-test tables [23] for the confidence level of 99 % and for the degrees of freedom n_1=1 and n_2= 26. In case of the regression model for the price of rough construction works, the value of F = 362.155 > Fkr is obtained, and so it can be concluded that its use is justified. In case of regression model for the time of construction, the value F = 75.137 > Fkr is obtained, and so it can also be concluded that the use of this regression model is justified.

Regression models for the price and duration of construction of a typical floor (Figure 3) represent results for well organised construction companies that employ competent technical experts and experienced work crews, and that use modern formwork systems [2]. For less organised companies, the results obtained in the paper can serve as target values to be aspired towards on future projects, which contributes to the implementation of this research in construction practice.

4.2. Leave-one-out-cross-validation

The applicability of regression models for predicting the price and duration of construction of new buildings was checked using the cross-validation procedure, which implies that the data set be divided into the training set and validation set [24]. The training set is used to form the assumed model, and the validation set to determine errors and accuracy of the model. As in this case we have a small sample of 28 buildings, the decision was made to use the leave-one-out-cross-validation (LOOCV) [24, 25]. In this particular case, the application of the LOOCV implies that one building be excluded from the set of buildings, and that the assumed model be formed on the basis of the data from the remaining n-1 buildings. In the next step, the value of dependent variable is calculated. This value is then evaluated and the evaluation error is determined. The procedure is repeated for all n buildings contained in the sample [24].

The regression model prediction accuracy was checked in the paper using the mean absolute error (MAE) [26], root-mean-squared error (RMSE) [27], and the normalised root-mean-squared error (NRMSE). The normalisation was conducted with respect to the mean value of the dependent variable and with respect to the range of values in the sample Y_{max}-Y_{min}, [26].

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|\hat{Y}_i - Y_i\right| \tag{6}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(\hat{Y}_i - Y_i\right)^2}{n}} \tag{7}$$

$$NRMSE_1 = \frac{RMSE}{\bar{Y}} \tag{8}$$

$$NRMSE_2 = \frac{RMSE}{(Y_{max} - Y_{min})} \tag{9}$$

The following results were obtained for the regression model for predicting the price of rough construction works: MAE=2,42, RMSE=2,74 (Table 6.), $NRMS_1$=2,55 % and $NRMS_2$=8,31 %.

The following results were obtained for the regression model for predicting the duration of construction of a typical floor: MAE=0,63, RMSE=0,86, $NRMS_1$=9,39 % and $NRMS_2$=18,41 % .

The results show that the quality of both models is satisfactory as to their prediction accuracy, although it should be noted that the regression model for the price of rough construction works is more accurate (lower NRMSE values).

5. Testing – case study

Research results were tested through a case study involving two buildings (No. 27 and No. 28) selected from the database [2]. These buildings were initially designed as massive structural systems with walls in both directions, but were subsequently redesigned into skeleton superstructure systems based on research results. New design solutions correspond to the proposed values of key parameters (Table 7). Market prices of the rough construction works and the duration of construction of a RC structure, were reduced, which shows that the research results presented in this paper are justified. The market price of rough construction works was reduced from 123.80 €/m² for massive structural system in both directions to 99.37 €/m2

Table 6. Use of LOOCV for regression model for predicting the price of rough construction works

Objekt	Xi = Fki	Yi = Ci	Regresijska jednadžba	Ŷi	$\hat{Y}_i - \bar{Y}_i$	$(\hat{Y}_i - \bar{Y}_i)2$
1	36.31	111.74	y = 0.3698x+93.7883	107.214	4.523	20.458
2	27.63	102.6	Y = 0.3690x+94.0363	204.232	1.634	2.672
3	28.52	102.04	Y = 0.3687+94.0803	104.594	2.553	6.516
4	25.77	100.85	Y = 0.3682x+94.1044	103.591	2.737	7.492
5	29.79	102.28	Y = 0.3688x+94.0857	105.073	2.796	7.815
6	34.9	103.91	Y = 0.3695x+94.0677	106.965	3.052	9.313
7	15.29	96.36	Y = 0.3658x+94.2150	99.810	3.447	11.884
8	26.56	102.97	Y = 0.3693x+93.9959	103.805	0.834	0.696
9	43.07	111.54	Y = 0.3691x+93.9111	109.810	1.731	2.997
10	39.75	112.99	Y = 0.3689x+93.8193	108.483	4.502	20.265
11	51.52	110.03	Y = 0.3723x+93.8193	113.150	3.117	9.714
12	54.2	112.29	Y = 0.3715x+93.9517	114.086	1.799	3.237
13	57.31	112.87	Y = 0.3725x+93.9517	115.285	2.412	5.816
14	11.54	96.72	Y = 0.3676x+94.0851	98.326	1.604	2.573
15	18.95	99.53	Y = 0.3683x+94.0851	101.036	1.506	2.267
16	18.75	98.83	y = 0.3677x+94.1020	100.996	2.167	4.697
17	16.39	104.07	y = 0.3744X+93.6290	99.766	4.301	18.502
18	22.75	106.29	y = 0.3728X+93.6941	102.173	4.113	16.919
19	9.12	97.82	y = 0.3705X+93.9025	97.282	0.537	0.288
20	13.1	99.48	y = 0.3707X+93.8906	98.746	35	0.540
21	2.54	95.66	y = 0.3713X+93.8629	94.805	0.858	0.735
22	10.1	100.03	y = 0.3720X+93.8087	97.499	2.527	6.385
23	9.97	99.14	y = 0.3720X+93.8087	97.517	1.622	2.632
24	72.52	120.79	y = 3697+93.3510	120.763	0.025	0.001
25	81.92	128.66	y = 0.3571X+94.2260	123.477	5.178	26.814
26	74.9	124.57	y = 0.3629X+94.0809	121.264	3.304	10.914
27	92.94	126.74	y = 0.3758X+93.8015	128.727	1.988	3.950
28	91.48	126.07	y = 0.3760X+93.7973	128.196	2.124	4.513
				Ukupno:	67.725	210.604
					MAE: 2.42	RMSE = 2.74

Table 7. Change of market price and duration of rough construction works for a typical floor in case of changing the superstructure system

Objekt	Izvedeno stanje/ Preprojektirano stanje	Utrošak osnovnih resursa			Direktni troškovi proizvodnje konstrukcije (struktura cijene)					Tržišna vrijednost konstrukcije [€/m²]	Tržišna vrijednost zidanja [€/m²]	Tržišna vrijednost GG radova [€/m²]	Trajanje raodva na konstrukciji [dan/etaža]
		beton [m³/m²]	armatura [kg/m²]	rad [h/m²]	materijal [€/m²]	oplata [€/m²]	kran [€/m²]	rad [€/m²]	ukupno [€/m²]				
27	masivni oba pravca	0.36	47.64	5.31	49.6	9.36	4.34	27.61	90.91	115.01	8.79	123.8	11
	skeletni	0.26	33.21	3.12	35.17	6.65	3.35	16.22	61.39	77.66	21.71	99.37	8
28	masivni oba pravca	0.36	46.52	5.14	48.99	9.36	4.34	26.73	89.41	113.11	8.63	121.74	10
	skeletni	0.26	31.05	3.36	33.98	6.65	3.35	17.47	61.45	77.73	22	99.73	8

(building No. 27), i.e. from 121.74 €/m^2 to 99.73 €/m^2 (building No. 28), while the duration of work was reduced from 11 to 8 days per floor (building No. 27), i.e. from 10 to 8 days per floor (building No. 28), which means that the price of works was reduced by approximately 20 % and the construction duration was reduced by approximately 25 %.

The redesigned buildings from the database were also used to check the accuracy of regression models from Section 4.1. The following values were obtained using the regression equation for the price of rough construction works: 98.15 €/m^2 for the building No. 27 (measured: 99.37 €/m^2) and 97.54 €/m^2 for the building No. 28 (measured: 99.73 €/m^2), which is within limits of the calculated standard error for regression (2.65 €/m^2).

The following values were obtained using the regression equation for the typical floor construction duration: 7.81 days per floor for the building No. 27 (measured: 8 days) and 7.56 days per floor for the building No. 28 (measured: 8 days), which is within limits of the calculated standard error for regression (0.79 day/floor). On the basis of the above, it can be concluded that the feedback from completed projects (key parameters values) into the design process can greatly improve the quality and rationalisation of design with regard to the cost and duration of construction work.

6. Application of research result in practical situations

The research considered in this paper is highly extensive and complex. It can be approached from the standpoint of an investor, but also from the contractor's standpoint. It can additionally be considered in individual phases of the project. Main results of this research are related to the selection of an optimum superstructure system, and to quantification of key parameters that greatly influence the price and duration of construction of RC structures. As practical implementation of these results can be diverse, only the main applications are given in the scope of this paper. This primarily relates to the improvement of the design process (use of PBD) and to the planning phase which is performed by the contractor.

6.1. Application of research results – phase of preparation of design documents

During projects execution, the investors and contractors (each form its own perspective) strive toward rationalisation of costs, realisation of the desired quality of work and reduction of schedules. The design phase is especially significant for investors, as it is in this phase that approximately 90 % of total savings on the project can be made [28]. On the other hand, the construction price offered by the contractor is dependent of design solutions, but also on the level of organisation of work and on the efficiency of the contractor.

The key step in the design phase is the establishment of the terms of reference that define in full detail required properties of the project, and the values of desired parameters. The limit consumption of concrete and reinforcement is proposed as a means of estimating quality of design with respect to construction costs [2]. The following values were adopted for limit consumption (Table 3):

- consumption of concrete ≤ 0,30 m^3/m^2,
- consumption of reinforcement ≤ 37 kg/m^2.

The mantion consumption values are valid for the dominant type of construction of residential projects in Belgrade.

Total working hours needed to complete rough construction should also be taken into consideration at the design stage. However, designers do not show interest in this aspect, and so the investor would have to engage experts in this area. Nevertheless, it can be concluded from the research results that the use of skeleton structure system also implies less working hours, which allows the contractor to bid a lower price for the works.

Research results are applied during design as it progresses. Thus, for instance, the selection of an optimum superstructure system is crucial at the stage in which the initial concept and conceptual design is being developed. The research shows that best results are achieved in the case of skeleton and mixed systems. The use of these systems creates preconditions in which the consumption of key resources can be kept within proposed limits. Furthermore, a rough estimate of consumption of concrete and reinforcement can also be made at this stage which allows easier comparison of various design concepts. Such approach is aimed at avoiding inadequate solutions already at the start of design process, as the price of any changes is the lowest at this stage, while the influence on cost is the greatest [29].

A more accurate consumption of concrete and reinforcement can be estimated during further elaboration of design, i.e. during preparation of preliminary design. At this stage the chosen design solution can be evaluated more accurately. If it is found that the solution does not comply with key parameters limits, then another preliminary design alternative has to be prepared. After main design is completed, accurate consumptions of key resources are available but, at that point, much time would have elapsed and considerable resources would have been spent on design, i.e. the price of changes would no longer be so low as at the start of the design process. The final cost-related estimate of the design solution is obtained after main design is completed. The estimate is done by comparing planned and realised values of key parameters. If the proposed consumption requirements are met, the client can initiate the contract-award process.

6.2. Application of research results –work planning phase

At the scheduling phase, the contractor attempts to organise its activities in the most rational way possible and reduce costs and durations. Such an approach enables the contractor to reduce the price of work, increase its competitive edge, and obtain the planned profit margin.

The contractor first plans the way in which it will realise the work at the bidding stage by considering all relevant factors that might affect the price and schedule. This is followed by detailed planning before the start of the works, the purpose being to define activities in such a way that will prevent any deviation from the schedule. To achieve a low price of work, the contractor must have at his disposal efficient formwork systems (Peri formwork [19] was used in this research) as well as properly trained and educated workers. In addition, the contractor must be capable of ensuring a high productivity of work, and must have personnel that is highly skilled in devising the work-progress optimisation techniques.

The required labour (total working hours needed for construction) is proposed as a measure for estimating schedule quality [2]. According to the data obtained from the database, the value of this parameter is limited to 3.60 h/m^2 (Table 3). This estimate is valid for the dominant type of residential construction in Belgrade. At that, it is important to clearly differentiate between the number of work hours originating from the design solution and the work hours derived from the schedule where possible idle time has to be taken into account. If the planned work time complies with the above mentioned figure, then the contractor can proceed to the realisation of work. If this is not the case, it is necessary to consider new options involving other formwork systems, different organisation of work, and a new progress schedule. When selecting the formwork system, the contractor's main criterion is the formwork purchase or renting price, the number of time the formwork can be used, and labour requirement. The correct selection of formwork system, with clearly defined concreting cycles, influences quite favourably the work flow, and eliminates unproductive work, hence leading to considerable savings [30-32]. In order to prevent and avoid unnecessary costs resulting from insufficient quality, appropriate quality management systems must be applied during realisation of works [33].

When defining the schedule, it is suggested to first elaborate short-term schedules for individual floors, and then to merge these schedules together to form an overall progress schedule. The objective of this approach is to ensure maximum employment and synchronisation of labour. Various scheduling systems can be used for short-term scheduling. The use of the planning system based on work cycles, i.e. the work cycle based scheduling (WCBS) [34] and the last planner system (LPS) [35], is suggested in this paper. The WCBS implies preparation of daily schedules with presentation of spatial distribution of work crews, synchronisation of work, and verification of the use of crew capacities on the daily basis. The LPS system is based on checking whether preconditions for realisation of activities are fulfilled [36], as well as on harmonisation of weekly schedules of last planners (persons in charge of the completion and control of individual tasks at the short-term level [37]) during weekly meetings.

As schedules for typical floors can be defined in various ways, the main requirement is not to vary the number of workers on the construction site, and to ensure maximum employment of every type of labour. The advantage is given to solutions involving greater effective employment of labour.

7. Discussion

The analysis presented in this paper is based on the data obtained from the construction company that performed construction works using its own labour in the city of Belgrade. The company used the formwork produced by a renowned manufacturer and achieved good-quality results. Such an approach was adopted so as to ensure high level of comparability of data and to enable easier identification of an isolated influence of the type of supestructure system on the price and time needed to build RC structure of a typical floor. This also enabled rational definition of key parameters that can conveniently be used by other companies as target values. The use of data from a single company also enabled development of excellent statistical indicators regarding reliability of results. On the other hand, there is a certain limitation of the analysis as it does not enable accurate determination of whether the company influences or the project influences are present in the regression analysis. That is why formation of a data panel (more companies from several projects in various time intervals) is proposed for further research. This would enable observation of the company influence (quality of labour, work organisation level, etc.) and the influence of the project in the context of duration (where the influence of technology could also be observed). It is also proposed that further research include the testing of results on a new set of buildings from other areas outside Belgrade. This testing would preferably include a greater number of variables, which would include the influence of various markets, and further improvement of research results presented in this paper.

8. Conclusion

The influence of superstructure systems on the cost and time for building RC structures is investigated in the paper. The research was conducted on the sample consisting of 28 residential buildings built in Belgrade, which represent the dominant type of construction used in this area. Based on main objectives and results of this research, the following conclusions can be made:

- The selection of the superstructure type greatly affects the duration and cost of construction of RC structures of residential buildings. The skeleton superstructure system, identified as the most favourable system, is followed by the mixed system, while the massive system in both directions is the least favourable system. The use of skeleton system results in savings when compared to other structural systems. Thus the savings in costs can reach up to 25 %, while time savings may amount to as much as 50 %.

- Key parameters that participate the most in the cost and time of construction of RB structures were identified. These parameters are: consumption of concrete, consumption of reinforcement, and duration of work per square meter. They together account for approximately 85 % of all costs considered in the study. The calculated values of key parameters enable comparison of design solutions and selection of the most favourable one.
- Limit values of key parameters where a building can no longer be considered rational were identified in the paper. This enables preparation of the properly quantified terms of reference, application of PBD, and measurable management and evaluation of design.
- Phased application of research results during design (from conceptual design to detailed design) ensures that correct decisions are made in early phases of design, when the price of changes is the lowest and the influence on costs is the greatest.
- Research results can successfully be applied for the improvement of schedules. The adequacy of work organisation and scheduling can be estimated by comparing the recommended work hours with planned work hours.

The implementation of research results and conclusions on real projects can result in an improved quality of design, better planning, proper optimisation of costs, and an improved efficiency in the overall realisation of works. From the standpoint of investors/clients, this contributes to the lowering of the project budget. From the contractors' standpoint, this practice increases competitive edge while also ensuring a greater profit margin. The implementation of research results in practice can contribute to the improvement of project management practices regarding rough construction works.

The research methodology presented in this paper can be successfully applied in different settings and for different types of buildings, and enables study of the influence of local specificities and construction methods on key parameters, i.e. on the cost and time for realisation of RC buildings.

Considering the significance of results obtained in this study, it would be useful to pursue investigations based on the same methodology for other types of work and for other types of buildings, and to consider and analyse the influence of positive contractor experience on the cost and time of construction of RC structures.

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