

Article

A Study of Factors Influencing the Compliance of Design Estimates at the Construction Stage of Residential Buildings

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Abstract: This article primarily addresses the factors affecting the possibility of achieving the costs estimated in the design stage of a building after its completion. The authors rely on an information base of twenty-three apartment buildings erected by twelve construction companies between 2017 and 2023, divided into two phases (2017–2020 and 2021–2023). The outputs of the article present the conclusions of several years of research into the identification of factors and risks affecting construction costs, capturing the development of price indicators over time, creating a realistic picture of working with costs from the building's design stage during its execution and the application of sustainable and digitalization technologies within a selected segment of the building industry. The presented conclusions are based on statistical dependencies compiled using regression analysis to explore the relationships between the cost, time and technological parameters of selected buildings. These outputs provide an interesting and well-founded perspective on the obtained data, thus overcoming the lack of relevant methods, techniques and fitting algorithms for a sophisticated and long-term approach to pricing in the construction sector.

Keywords: Building Information Management; cost estimate; price indicator; regression analysis; residential development; risks; sustainable construction



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1. Introduction and Literature Review

1.1. Introductory Information

This article primarily addresses the factors affecting the possibility of achieving the estimated costs specified in the design of a building after its completion. The outputs of the article, resulting from several years of research, are directed mainly towards the academic community and the professional public engaged in the field of cost management, mainly in working with data. In general, work with data is limited by the insufficient amount of both up-to-date data reflecting market developments in the field of residential development and relevant methods, techniques and algorithms enabling a sophisticated and long-term approach to collecting and evaluating this information. Therefore, the article presents some interesting data sets and approaches their interpretation based on the relationships processed by regression analysis. Another output of the article explores the possibilities of applying modern trends in residential buildings. This particularly refers to the field of digitalization and sustainability, which are currently becoming increasingly iterated, both in terms of raising environmental awareness and the search for cost savings in the design, execution and operation stage of buildings.

Every company wants to be in full control of its pricing policy so that it can perform at its best. Unlike other industrial segments, in the building industry, each building is unique, and estimating its cost at the design stage is a challenging discipline. Even with the use of the most advanced methods and tools, it is almost impossible to achieve exactly one hundred percent of the cost from the design (preparation) stage after the project has been completed. An example of one such option that can significantly help to get

at least as close to this figure as possible is the digitalization representative: Building Information Management (BIM). This article works with data collected from completed apartment buildings with estimated costs from EUR 2.5 to 6 million located in Prague, Ostrava and Brno (Czech Republic) and their close surroundings. In these buildings, BIM, or the digital building model, respectively (i.e., a 3D model enriched with non-graphical data; also a BIM model), was in many cases part of the building design. The data set includes twenty-three apartment buildings that were part of a research project of the Centre for Advanced Materials and Efficient Buildings at the Czech Technical University in Prague (CTU) and constructed by twelve building companies in 2017 to 2023 (i.e., project completion). In almost all cases, these are construction projects with several above-ground and underground storeys. The article addresses cost estimation exclusively from the perspective of the general contractor (also referred to as the contractor) of the buildings within the Design–Bid–Build delivery method for a private investor (builder). This is a traditional contracting method used in the Czech Republic (CR), where the builder provides detailed design documentation with the necessary permits from the relevant authorities. Within the tendering process (competition for the contract), the bidder (potential contractor) is invited to offer a bid price for the released design documentation, including other terms and conditions of the contract. The cost estimation practice commonly used in the Czech Republic applies the construction budget, whose structure is based on the format of local pricing systems, i.e., on the Classification of Structures and Works (CSW). In the research, “only” the core structures of the construction projects, i.e., apartment buildings, were monitored (i.e., excluding associated structures at the level of connections to public utilities, outdoor parking spaces, fencing, etc.). At the same time, the representatives of the respondents (contractors) commented on the risks that mostly affect the change in the cost estimates from the design stage during the implementation process. It should be noted that Czech construction companies were not very willing to release such sensitive data, but they eventually succumbed to the calls of the academic community and were guaranteed anonymity. The obtained data were processed using different mathematical/statistical techniques and indicators.

Several situations occurred throughout the entire monitored period (2017–2023) that had a significant impact on society as a whole and thus on pricing in the building industry as well. These included mainly the health crisis caused by the COVID-19 Pandemic in 2020 to 2022, the ongoing armed conflict in Ukraine starting in 2022 and the associated significant growth in inflation rates in the last two years. Figure 1 shows these impacts graphically and in value terms as compared to previous years through year-over-year changes in the construction cost index and inflation rates for the Czech Republic and the European Union (EU) since 2015. A principal change in the annual construction cost index took place in 2022, i.e., towards the end of the COVID period and the beginning of the war in Ukraine. This year-over-year increase represented a soar of 13%. However, from 2023 onwards, we have been observing a gradual year-over-year decline in this index and in the inflation rate as well, not only in the Czech Republic but in the EU, too. This observed trend also continues in this year, 2024. In the figure below, the correlation between the construction cost index and the inflation rate in the local market in recent periods can be seen. However, it is evident from the values shown that the construction sector is “failing” to catch up with the annual inflation rate increase in the Czech Republic since 2021. At the same time, the year-over-year change in the inflation rate development in the Czech Republic in 2021 and 2022 was at least double the EU average.

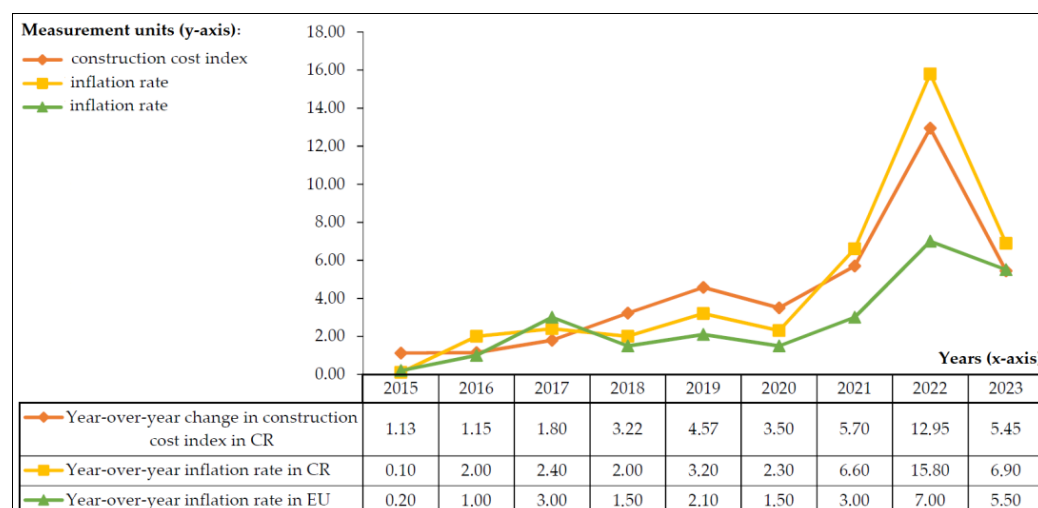


Figure 1. Year-over-year changes in the construction cost index and inflation rates [1,2].

1.2. Definition of Research Problems

Based on the above introduction, the authors have identified the following research problems to which the conclusions of the article are directed:

1. What are the degrees of dependencies between the data obtained for the monitored apartment buildings? This question was investigated in terms of the following:
 - The size of an apartment building and the price indicator per 1 m³ of built-up space;
 - The size of an apartment building and the cost estimate value from the design stage achieved during execution;
 - The variability in the price indicator per 1 m³ of built-up space over time;
 - The variability in the price indicator per 1 m³ of built-up space and the cost estimate value from the design stage achieved during execution;
 - The variability in the cost estimate value from the design stage achieved during execution over time.
2. What factors and risks affect the issue of cost estimation during preparation and the costs achieved during execution?
3. What digitalization methods could help to refine the cost estimates from the design stage? How often are these methods applied in practice?
4. What sustainable technologies are currently being applied in the apartment building segment? Or, potentially, what are their implications for the values of price indicators and the differences between design cost estimates and execution costs?

1.3. Cost Estimate

Estimating the cost of a construction project is becoming an increasingly challenging discipline given the dynamics of the surrounding socio-political effects and the gradual incorporation of new trends in the form of sustainable technologies. The key to a successful estimate is, among other things, a high-quality source of information. Within the construction segment, there are several pricing databases, usually linked to local standards, created by private engineering organizations. They are, for example, the Building Cost Information Service [3], with nationwide coverage in the UK, or the Baupreislexikon pricing database [4] operating in Germany, where the data are broken down by the federal states, and the ÚRS pricing database [5], which is of key importance in the Czech Republic, and most construction budgets are based on it.

Nevertheless, these databases are primarily of indicative value, being based on data from previous periods provided by respondents representing construction companies, real estate developers, builders, etc. The approximation of the estimates in question is the

responsibility of the bidding departments in construction companies or, once the contract has been awarded, of the teams associated with the actual implementation. Their aim is to incorporate their subcontractors' prices, company mark-ups, trends and price forecasts for various construction commodities, supplemented by their own experience from previous projects, into their calculations [6]. In general, there are not many up-to-date articles dealing with different methods of data collection [7], data evaluation [8] and setting up key factors affecting cost estimation in the building industry [9]. This implies a certain absence of a higher frequency of research studies/articles on the current issues of the factors affecting the differences between the cost in the preparation and the execution stage, bringing data on the implementation of current trends in residential development. One of the articles introducing sophisticated methods related to these issues is [10]. Its authors describe the Equipment Cost Rate (ECR) method based on machine learning and data collection, which helps predict costs in the design of a building with respect to the building's future maintenance. Another article addressing cost estimation during preparation compared to the project's execution stage is focused on the evaluation of obtained data based on descriptive statistics, the Kruskal–Wallis H test, exploratory factor analysis and partial least-squares structural equation modelling (PLS-SEM). Its authors base their analysis and conclusions on the 27 university building projects that they studied, pointing out that 25 projects (i.e., 93%) experienced cost overruns of 7% on average for various reasons. They cite poorly drafted construction cost estimates in the design stage, together with inadequate contractual terms for the builder, as the key cause [11]. The authors of the article ("A study of factors influencing the compliance of design estimates at the stage of construction of residential buildings") also compare their findings with the above conclusions with respect to another segment of the civil engineering industry, i.e., residential development. In general, these outputs from studies and analyses dealing with cost estimation should primarily lead to their improvement and the increased efficiency of their generation. The current trend in cost estimation in the Czech Republic is so-called parametric estimation in construction, based on the input information/parameters of a respective building and documented price data [12]. This parametric estimation can work with various data inputs, e.g., a digital model of the building [13], where the automated collection of information from various databases can be set, e.g., in the form of price indices of construction works released by the relevant statistical offices [14]. This issue is also presented in numerous other international publications, frequently using different approaches [15,16].

1.4. Building Digitalization

The BIM method, which has been known for several years, is still a new concept in the construction sector, representing a significant technological advance in information technology [17]. It combines a digital environment with a real one and has a great potential to change traditional working procedures in the preparation, construction and management of buildings [18]. The BIM method has several definitions formulated by leading experts in the building industry and building associations. The most frequently cited interpretation according to the authors of this article reads as follows: "BIM is a process for creating and managing information on a construction project throughout its whole life cycle. As part of this process, a coordinated digital description of every aspect of the built asset is developed, using a set of appropriate technology. It is likely that this digital description includes a combination of information-rich 3D models and associated structured data such as product, execution and handover information. Internationally, the BIM process and associated data structures are best defined in the ISO 19650 and 12066 series of standards [19]."

In general terms, the BIM method definition has common denominators in the form of the following:

- A single environment shared among the different participants in the construction process through the so-called Common Data Environment—during preparation, construction and management;
- A 3D view of the building or the entire project, including non-graphical data;

- More effective decision making related to project management bringing economic benefits.

The interconnection between the BIM method and construction cost estimation issues is the subject of many articles [20], being often referred to by the BIM5D abbreviation [21]. These are mostly publications focusing on the development of the Quantity Takeoff [22] and the Bill of Materials [23], using as much automation as possible, primarily at the level of obtaining the quantities of structures via a digital building model [24]. Also, these articles describe how to link local pricing practices with various classification systems applied in the creation of a digital building model, allowing data to be classified according to selected criteria, e.g., by the structural system, location of a structure in the building or the construction project itself, etc. In the article “Incorporating Context into BIM-Derived Data—Leveraging Graph Neural Networks for Building Element Classification”, the applications of the classification were verified in a study where 42,000 elements were classified. This significantly helped with the subsequent work on the data recorded in the digital building model [25]. CCI, COCLASS, Uniclass and Omniclass are the most used newly emerging classification systems [26,27]. These are new classifications intended to support digital development. Related to this article is an interesting publication [28], which also addresses the BIM5D issue in relation to minimizing cost overruns from construction preparation in a railway environment. The authors comment on the unsatisfactory progress in the standardization of the building industry and the associated definition of a graphical and non-graphical detail of the BIM model for various project stages, which impedes the maximum possible efficiency of work. However, in their conclusions, the authors fully support the incorporation of the BIM method in cost estimation issues, even in its current form, as do some other authors [29,30]. The authors of this article also place great emphasis on the BIM method in relation to solved issues, where the digital building model has become a valuable source of information in research.

1.5. Sustainability in Construction

Materials that are to be as sustainable as possible and as energy-efficient to produce as possible are beginning to enter the requirements for modern buildings (not just residential ones) in a significant way [31]. The sustainable construction trend, together with digitalization, appears to be one of the most topical issues, both in research and in construction practice [32]. A current drawback is that most sustainable or innovative materials lack the necessary database related to cost estimation issues [33]. In many cases, building contractors must approach only a limited portfolio of manufacturers and, given the dynamic price development of different resources for production and the limited possibilities of substituting these materials, there are considerable risks [34]. The article itself does not directly address the impacts of sustainable materials and technologies on pricing. However, in the construction projects where they were applied, a higher value of the price indicator per 1 m³ of built-up space was identified (though there are more potential reasons—for details, see Results and Discussion). The digital model of a building, which includes the technical and informational parameters of individual elements, is offered as a “helper” in the search for substitute sustainable materials and for compiling the evaluation of buildings by various certification bodies (e.g., the Leadership in Energy and Environmental Design and Building Research Establishment Environmental Assessment Method) [35]. Interesting construction projects combining sustainability issues with the BIM method have recently been completed in Asia (particularly in China and Malaysia) [36]. The authors of published articles state that the incorporation of the above two issues into large-scale projects was a strategic decision, primarily to determine the degree of sustainability of the buildings in question and in relation to their future management and maintenance [37]. The available conclusions of individual articles assess the benefits and negatives of incorporating these topical issues into the projects themselves, and the authors agree that the benefits for the contractor and for the builder clearly prevail [38]. Among other interesting Asian projects, there is research conducted on the use of BIM and sustainability issues in high-rise build-

ings (mostly residential), publicized by experts from Korea [39]. The presented results were combined with the compilation of Critical Success Factors (CSFs) for the application of these new topics to building structures. The authors state that their results are supported by a survey of 205 construction projects. These Critical Success Factors (CSFs) include, among others, factors associated with increased productivity and efficiency, reduced project cost, better cost estimates and control, reduced claims and litigation risks, etc. In general, BIM and building sustainability topics have seen significant progress measured by the articles published in recent periods, which can be proved by the above-mentioned references.

1.6. Summary of Literature Review

The literature review focused primarily on the articles and publications published in international scientific databases with impact factors. The chief reason is their high professional quality (each article undergoes a rigorous peer-review process). Also, there is a shortage of other up-to-date sources, mostly books, specialized in the areas of construction production pricing, cost management during construction or cost management in relation to Building Information Management and sustainability. The literature search produced several propositions, summarized by the authors in the following points:

- In general, there are not many up-to-date articles dealing with different methods of data collection, their evaluation and the setting of key factors affecting cost estimation in the building industry. Therefore, among others, the authors of this article perceive their published data as beneficial to the academic community.
- The key to successful cost estimation is current market information with some time-lagged prediction of future development. Within the construction segment, there are several cost databases, usually linked to local standards and produced by private engineering organizations. Nevertheless, these databases cannot be fully applied by construction companies, and they must always conduct their own market monitoring and price calculations according to their capabilities and resources.
- The current trend in cost estimation is parametric estimation in construction, based on the input information/parameters of a respective building and the documented price data. This discipline allows for the development of costs based on a few inputs about a future structure in its early design stages. However, a comprehensive corporate database from the company's past projects and the proper evaluation of market trends are necessary.
- The BIM digitalization method in the form of a digital building model brings, among other things, the opportunity to increase the efficiency of cost estimation during production and the probability of cost compliance during the execution stage. However, the digital building model of a building is not the standard practice for all construction projects, and excessive standards for its creation are still being developed. This situation is likely to continue in the traditionally conservative building industry for several more years.
- The sustainability topic is gradually gaining momentum, both in terms of the search for "green solutions" to increase environmental friendliness and cost savings, particularly in the operational stage of the life cycle, and, more recently, the intensification of the requirements arising from legislation and the banking sector. A current drawback is the fact that most sustainable or innovative materials lack the necessary database related to cost estimation issues, which introduces a certain degree of risk and uncertainty. According to the reviewed publications, Nordic European countries (especially Norway, Denmark, Sweden) and selected Asian regions (e.g., Malaysia and Korea) seem to be leaders in the application of sustainable technologies. The authors of this article provide information on sustainable technologies and the frequency of their application in residential development on the Czech market and how "successful" it is to estimate the costs of the respective technologies during building design.

In general terms, this article seeks to address the above-mentioned lack of current research studies on the factors affecting the differences between the costs of preparation and

the execution costs, supplying data on the implementation of current trends in residential development.

2. Materials and Methods

2.1. Structural and Technological Design of Selected Apartment Buildings

The selection of the buildings included in the research was carried out in cooperation with construction companies. They usually included apartment buildings with similar structural (design) solutions constructed by these companies during the monitored period (for more details about the structural solution, see the next paragraph). According to the available statistics, an average of 31.6 apartment buildings per year were completed in the selected cities (Prague, Brno and Ostrava) between 2017 and 2023. Their built-up space volume ranged from 5000 m³ to 12,000 m³, and they had a similar structural (building) design [40] (a graphic example of selected apartment buildings is shown below in Figure 2). In total, 221 apartment buildings were monitored, which means that approximately each tenth (exactly 10.4%) building completed during the period under study participated in the survey. From the authors' point of view, this is a relevant sample regarding the fact that the necessary data can or rather cannot be obtained easily from the companies that are involved. It must be remembered that companies provided very sensitive information about their construction costs, and if it were not for the research project and the necessary confidentiality agreements, no data would have been released. Considering the propositions obtained from the literature review, the authors believe that the conclusions presented are sufficiently conclusive for the respective section of the construction segment within the period under study.

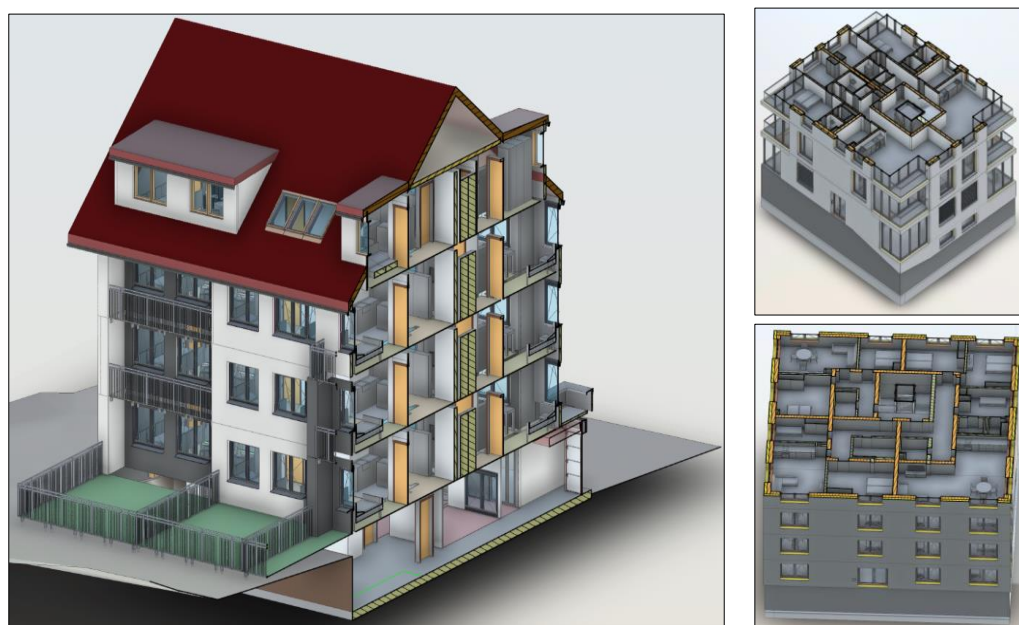


Figure 2. Selected apartment buildings in the “BIM environment” (an example of research data).

Typically, these were apartment buildings with one or two underground stories (garages and cellars) and several storeys above ground (apartment units and common areas). The composition of the apartment units ranged from 1+kitchenette to 4+kitchenette. The structural design of the apartment buildings was usually based on piles, a monolithic concrete skeleton filled with concrete or ceramic blocks with a flat roof (or so-called “green” roof in exceptional cases, or, in minority cases, with a pitched roof). Lightweight cladding or an ETICS (external thermal insulation composite system) always fitted with thermal insulation was used as the external wall finish. Gypsum plaster was applied on the interior of the apartments and common areas. The fillings of openings (windows and doors) were made of metal or plastic frames with double or triple glazing. As a rule, gas condensing

boilers were used as a heat source, or the apartments were connected to district central heating. However, in the latest residential projects designed from 2020 (when national legislative requirements for new developments were amended), more sustainable technologies have been applied. They involved combinations of gas condensing boilers with plate solar thermal collectors, or heat pumps with electric boilers. These technologies usually represent new options for heating sources, usually in conjunction with forced air exchange, so-called heat recovery. Selected, usually taller houses had a lift as part of their itinerary.

The reuse of wastewater, so-called grey water, was evaluated as a minimally applied sustainable technology. Of the apartment buildings that were the subject of the research, there was only one that had incorporated this technology into its design. The limiting factor of this technology is the relatively low purchase price of water (average price in Q4/2023 was 2 EUR/m³ in Prague). Therefore, it is still economically unviable to use grey water recovery technology in apartment buildings. Compared to the traditional method of sewage disposal, the builder must invest in more pipelines, more spacious utility shafts, including space requirements in technical rooms, and technologies for water treatment itself.

2.2. Factors and Risks

Construction practice has its own specific risks that must be considered when developing a cost estimate. Their identification and the measures proposed are individual; each company has its own way of dealing with them and incorporating them into its pricing policy. Within the scope of this article, the authors focus on the identification of such risks that may affect the difference in the cost estimate between the design and the execution stage of a construction project. The specific selection of risks was obtained through the Delphi method. Thirty-two experts (respondents) from twelve construction companies with an annual turnover of more than EUR 40 million were involved in the survey, providing data for the research project in two years, i.e., 2017 and 2023. Each respondent identified the factors and risks and assigned them impact magnitudes on a scale of 1 to 10 (1—negligible, 10—quite significant) and the probability of occurrence. Based on the responses received, the following factors and risks were identified for the two years studied (2017 and 2023):

- Inadequate quality (detail) of detailed design documentation;
- Incorrectly calculated construction budget with the bill of quantities;
- Contractual penalties, non-compliance with contract terms and penalization by the investor;
- Appearance of extra work or less work;
- Subcontractors' coordination;
- The unavailability of materials;
- Quick growth in construction material prices.

The main factors and risks affecting cost estimates with a constant occurrence in the Czech building industry are inadequate quality (detail) of project documentation, an incorrectly calculated construction budget with the bill of quantities and contractual penalties by the investor. In contrast, the risks associated with subcontractors and the occurrence of extra work or less work occurring in 2017 were replaced by the risks associated with the unavailability of and price increases in construction materials a few years later (2023). This reflects the socio-economic situation and gradually rising inflation rates in the Czech Republic.

The coordination of subcontractors is a type of risk associated with the Czech environment, where the absolute majority of general building contractors execute the majority of their production through specialist companies. These subcontractors are authorized to do the work that the general contractor is unable to provide from its own sources, either due to unavailable labour capacity or the absence of the necessary machinery. As a rule, a dozen different trades are involved. It is precisely because of this fact (significant dependency on several collaborating contractors) that the risk was identified as a significant "player" affecting the construction cost estimate. In recent years, however, subcontractors'

coordination has fallen down the scale of significant risks in light of other rather socio-economic issues.

The numerical expression of price increases for specific building materials is illustrated above (Table 1) for key components in the construction of apartment buildings using the so-called composite index. This index is calculated as the product of monthly indices representing decreases or increases in individual prices. Within the 2021–2023 period, the most price-volatile building materials (reported increases of 50–80%) were steel reinforcement for concrete, polystyrene foam insulation products for buildings or EPS (e.g., EPS boards for the facade and floors), burnt masonry elements (e.g., ceramic cut blocks) and ceramic tiles. The values identified effectively confirm the significant role of risks associated with building materials over time.

Table 1. Composite index of selected building materials and products for the period of 2021–2023 in CR [41].

Material/Product	Composite Index 2021–2023
fresh concrete	1.436
steel reinforcement for concrete	1.835
grown structural timber	1.117
concrete masonry element	1.420
porous concrete masonry element	1.404
burnt masonry element	1.584
concrete masonry element	1.420
ceramic tiles	1.539
insulation product of polystyrene foam for buildings	1.697
gypsum fibre board	1.456

2.3. Digital Building Model

The digital model of a building is one of the key tools that can reveal qualitative deficiencies in project documentation in the building design stage and thus significantly reduce the likelihood of collision points between individual structures during their execution (a graphical and non-graphical example of the data of selected apartment buildings is shown below in Figure 3). At the same time, the BIM model significantly refines and streamlines the creation of the bill of quantities, which has a significant impact on cost estimation. During the execution stage, it can then be used by the investor and the general contractor for the verification process of the quantity of performed works submitted by the collaborating company as part of the approval of the work performed, intended as a basis for invoicing.

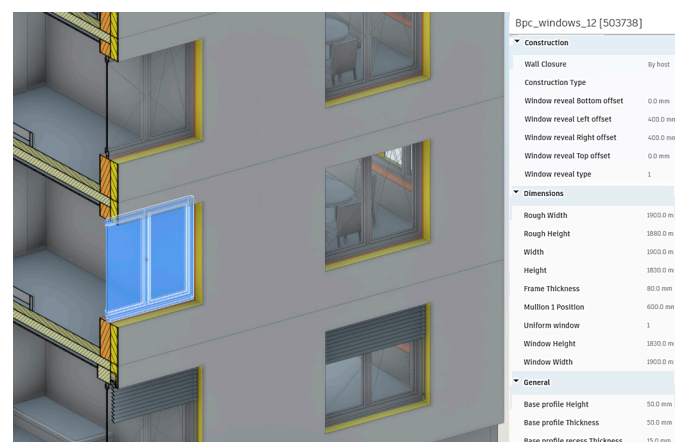


Figure 3. Digital model of a building: graphical and non-graphical representation (an example of research data).

The benefit of the digital building model with a link to the preparation of the bill of quantities and subsequently to the construction budget is associated with the highest possible level of automation. That means the least laborious transfer of data from the BIM model to the specific items of the bill of quantities or the construction budget. Currently, however, it is a rather “semi-automated” information transfer between the “BIM” design and the applied pricing software. This semi-automation usually consists of exporting quantities and other technical information about individual elements from the “BIM” design software into a spreadsheet process. Here, after data editing, the data are imported into the pricing software and various reports and budgets are subsequently produced (the graphical representation of the semi-automation process is shown in Figure 4). To achieve an “ideal” state, i.e., automated data transfer into the itemized structure of the bill of quantities/construction budget with the most accurate possible quantities, at least two prerequisites related to the standardization of the building industry must be met. The first condition is the appropriate choice of the graphical format of individual elements, where the Level of Geometry (LOG) methodology is currently the most widely used. The second condition is the inclusion of appropriate non-graphical data leading to obtaining the necessary information about the element to enable automation.

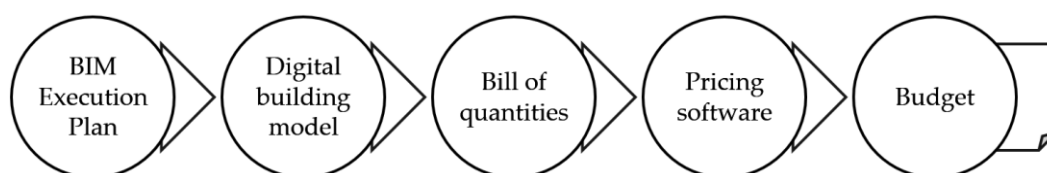


Figure 4. “Semi-automation” in the approach of using data from the model in reporting and budgeting [42].

Typically, each country has its own national classification system (also referred to as a CS) or at least a conventional structure of the classification of building structures/works. Unfortunately, these traditional classification systems are of limited use for modern data handling in a 1:1 (element = item) relationship. In the Czech environment, this is the Classification of Structures and Works (CSW), acting as the basis for the pricing systems issued by engineering companies. It is time-consuming and therefore costly to draw a BIM model so that it can be fully entered in the CSW structure, which has a high level of detail. Thus, in many countries, there is a move away from these traditional classification systems and new ones are replacing them, such as Uniclass 2015 in the UK, CoClass in Sweden, etc. [43].

The digital building model was assembled as part of the research conducted for only a few apartment buildings, mostly built in recent periods, where its possible effect on the cost estimate is unfortunately inconclusive. Or, alternatively, for buildings with a BIM model, we cannot determine that, thanks to this fact, smaller differences in the cost estimation (preparation vs. execution) were achieved, especially because of the year-over-year inflation rates and increases in the prices of construction works between 2021 and 2023. After the project completion and creation of the as-built construction using the BIM model (including client’s changes), this digital model of the building should be used for the management and maintenance (facility) of individual component parts. However, the survey reveals that general contractors and developers (investors) no longer play a significant role in these operational stages. This is because the apartment buildings are sold, and they are therefore not very motivated to create this model in the required quality.

3. Results and Discussion

3.1. Overview of Results

The results of the research are interpreted mainly through the cost estimate percentage value from the design achieved after the execution stage and the price indicators related to 1 m³ of built-up space. The inputs were obtained from collaborating respondents within the

research project conducted by the Centre for Advanced Materials and Efficient Buildings, with the proviso that the name of the company and the building projects in question had to be anonymized (these being irrelevant data for the purposes of the article). The survey involved apartment buildings with built-up spaces between 5000 and 12,000 m³ of a similar construction standard level (the difference being primarily at the level of used technology), built between 2017 and 2023. The calculated data were processed into a table (Table 2) split into two phases, i.e., 2017–2020 (completed design from 2014 and execution by 2020) and 2021–2023 (completed design from 2018 and execution by 2023). These data were supplemented with information on the applied technology for heating, forced ventilation, power source and other construction project details (e.g., green roof, wastewater reuse, BIM model).

Table 2. Compliance with the cost estimate from design after the execution stage.

	Apartment Building Marking	Built-Up Spaces [m ³]	Achieved Value of Cost Estimate from Design [%]	Applied Technologies
Completion by 2020	A	10,362	90	GCB/L
	B	6237	92	HCP
	C	7047	93	GCB/L
	D	5154	108	HCP
	E	9607	95	GCB/L
	F	7222	98	HCP/BIM/L
	G	5370	103	GCB/L
	H	9012	96	GCB/L
	I	6829	95	GCB
	J	7353	93	GCB/L
	K	5696	97	HCP /BIM
	L	8838	94	GCB/L
	M	6984	93	HCP /L
	N	11,383	96	GCB/L
	O	6763	101	GCB+FVE
Completion by 2023	P	11,029	107	GCB+FVE/CR/L
	Q	8043	99	BIM/GCB+FVE/CR/L
	R	4823	107	GCB+FVE/CR
	S	7968	105	BIM/HP+EB+FVE/CR/L
	T	7418	113	HP+EB/CR/L/GW
	U	6784	112	HP+EB/CR/L
	V	10,659	107	BIM/GCB/GF/CR/L
	W	5635	109	BIM/GCB/L

Legend: GCB—gas condensing boilers; HCP—district central heating (heating plant); L—lift; FVE—photovoltaics; HP—heat pump; EB—electric boiler; CR—central heat recovery; GF—green roof; GW—grey water; BIM—model.

The calculated data (see Table 2) show that the first monitored period (2017–2020) was significantly more stable, achieving more accurate cost estimates from the design in the post-construction stage (within 5% on average (the arithmetic mean is meant in all occurrences in the article)) than in later years (2021–2023). At the same time, these estimates from the design were exceeded minimally in the execution stage, i.e., the achieved cost estimate value from the design was less than or equal to 100%. This phenomenon occurred in only 3 cases out of 15 (i.e., every 5th construction project), where the average ranged around 96% (median of 95%). In contrast, in the second monitored period (2021–2023), the cost estimate from the design was exceeded in almost all cases during the execution stage. Only one construction project “managed” to fall below the 100% threshold, but very narrowly (99%). The average and the median of the cost estimate from the design stage were at a level of 107% during this period. This means that the general contractors of the respective buildings failed in achieving the planned cost estimates from the design stage during the construction. These findings are indicative of the dynamic period that we have been witnessing in recent years. Unfortunately, the general contractors in construction

and probably no other entity in the procurement network had been able to predict these developments (a graphical interpretation of the data from Table 2 is below in Figure 5).

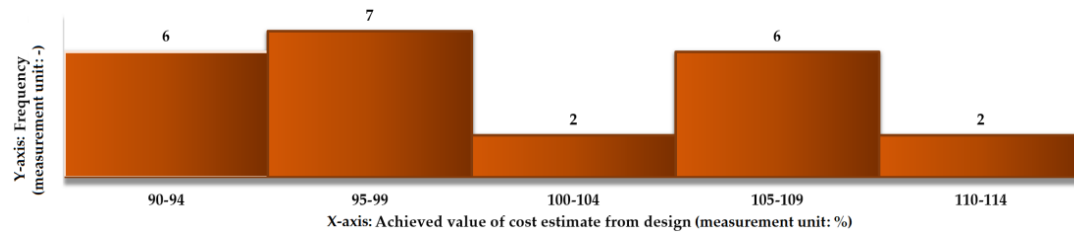


Figure 5. Frequency histogram graphically summarizing the results in Table 2.

The cost estimation accuracy level (design vs. execution) is generally evaluated as an indicator of the correct setting of the system of work of any construction company, which is crucial for its operation. In the Czech Republic, there is no generally valid fixed threshold that determines which achieved values (design vs. execution) are considered acceptable and which are not. Naturally, if the cost estimate from the preparation stage is of a higher value than that after construction, it is a significantly better situation for the general contractor. However, the downside of this situation is the possible limit in competition (tendering) for the contract. Unjustified higher costs resulting from the design of the building may lead to failure in a competitive environment, i.e., not winning a tendered contract. Conversely, if the cost estimate from the preparation is lower than that in the execution stage, the general contractor is in an awkward position and in many cases must communicate with the investor to address the source of the imbalance in relation to the contractual terms. From the survey conducted, the respondents indicated a 3% difference between the cost estimate from the design and after the execution as acceptable, i.e., up to 103%. This (above 103%) corresponds to 8 construction projects out of 23 (see Table 2) that participated in the survey.

In the period of 2017–2020, the price indicator per 1 m³ of built-up space averaged EUR 233 in the design stage and EUR 225 in the execution stage. In the second period of 2021–2023, the price indicator averaged EUR 297 in the design stage and EUR 320 after execution. Overall, there was a significant increase in the respective price indicator between the assessed years (2017–2023), where the difference between its lowest and highest value from both the design and execution was EUR 183, i.e., showing a more than 100% increase over 6 years of data collection (in more detail about the identified price indicators below in the Table 3). This increase is linked to several factors related to socio-economic aspects, requirements for the integration of sustainable technologies and lower energy intensity of buildings, etc.

Table 3. Price indicators from the design and after the execution stage.

Apartment Building Marking		Design-Execution (End of Stage)	Price Indicator–Design [EUR/m ³]	Price Indicator–Execution [EUR/m ³]
Completion by 2020	A	2014–2017	209	189
	B	2014–2017	193	178
	C	2014–2018	218	203
	D	2015–2018	201	218
	E	2015–2018	218	207
	F	2015–2019	232	228
	G	2015–2019	244	252
	H	2016–2019	244	235
	I	2016–2019	240	229
	J	2017–2020	254	236
	K	2017–2020	238	232
	L	2017–2020	254	239
	M	2017–2020	238	222
	N	2017–2020	254	244
	O	2018–2020	255	258

Table 3. Cont.

	Apartment Building Marking	Design-Execution (End of Stage)	Price Indicator–Design [EUR/m ³]	Price Indicator–Execution [EUR/m ³]
Completion by 2023	P	2018–2021	267	286
	Q	2018–2021	271	269
	R	2019–2021	263	282
	S	2019–2022	330	347
	T	2019–2022	319	361
	U	2020–2022	319	358
	V	2020–2023	308	330
	W	2021–2023	296	323

3.2. Responses to Research Problems

In the introduction to this article, the authors identified several research problems which became the focus of their work. Within this chapter, these problems are addressed one after another and the findings are compared with the conclusions published by other authors (especially from the literature review). For the sake of clarity and clearer interpretation, the authors have decided to briefly respond to each research problem separately along with a commentary on other authors' conclusions first, and only later do they describe their individual findings more comprehensively (Section 3.3).

1. What are the degrees of dependencies between the data obtained for the monitored apartment buildings?

The responses to the first problem are grouped into areas of interest by bullet points. The degree of correlation itself was defined at two levels according to the value of the correlation coefficient, as independent (statistically insignificant dependency) and dependent (statistically significant dependency).

- The degree of correlation between the size of an apartment building and the price indicator per 1 m³ of built-up space:

In both phases, no statistical correlation between the respective parameters could be found. The obtained results can be seen in Figure 6 below. In the first phase, a statistically insignificant dependency between the increase or decrease in the price indicator and the increase or decrease of the built-up space (different for design and execution) is visible at the level of the design and execution of the apartment building. In the second phase, this phenomenon also occurs, but only for execution. The preparation is nearly constant when the trend line is plotted, i.e., completely uninteresting in terms of dependency. In all stages, however, an independent degree is found.

Compared to the findings in other articles and publications, the connection between the size of an apartment building and the price indicator value is usually present. Specifically, the larger the built-up space of an apartment building, the lower the price indicator value (particularly in the design) [14,15]. This generally makes more sense in relation to potential quantity discounts, e.g., for building materials, etc. However, in the Czech environment, this link has not been of relevance. The authors of the article explain this by the fact that the respective discounts had already reached their limits for smaller apartment buildings and therefore the expected dependency for larger ones was not manifested. Another slight difference between this article and other sources was found in the application of the price indicator per 1 m² of the floor area, which is, in principle, similar to 1 m³ of built-up space, which has a historical origin in the Czech Republic and is still applied.

- The degree of correlation between the size of an apartment building and the cost estimate value from the design achieved during execution:

In the first phase, the correlation between the size of an apartment building and the difference in the design versus execution costs became apparent. Specifically, the lower the value of the built-up area, the more likely 100% of the design cost estimate was achieved during execution. It is therefore a dependent degree of correlation. For the second phase,

an independent degree of correlation was identified. Here, the obtained data slightly tend to suggest that if the built-up area decreases, the probability of running over 100% of the cost estimate from the design stage during execution increases. The results obtained can be seen in Figure 7 below.

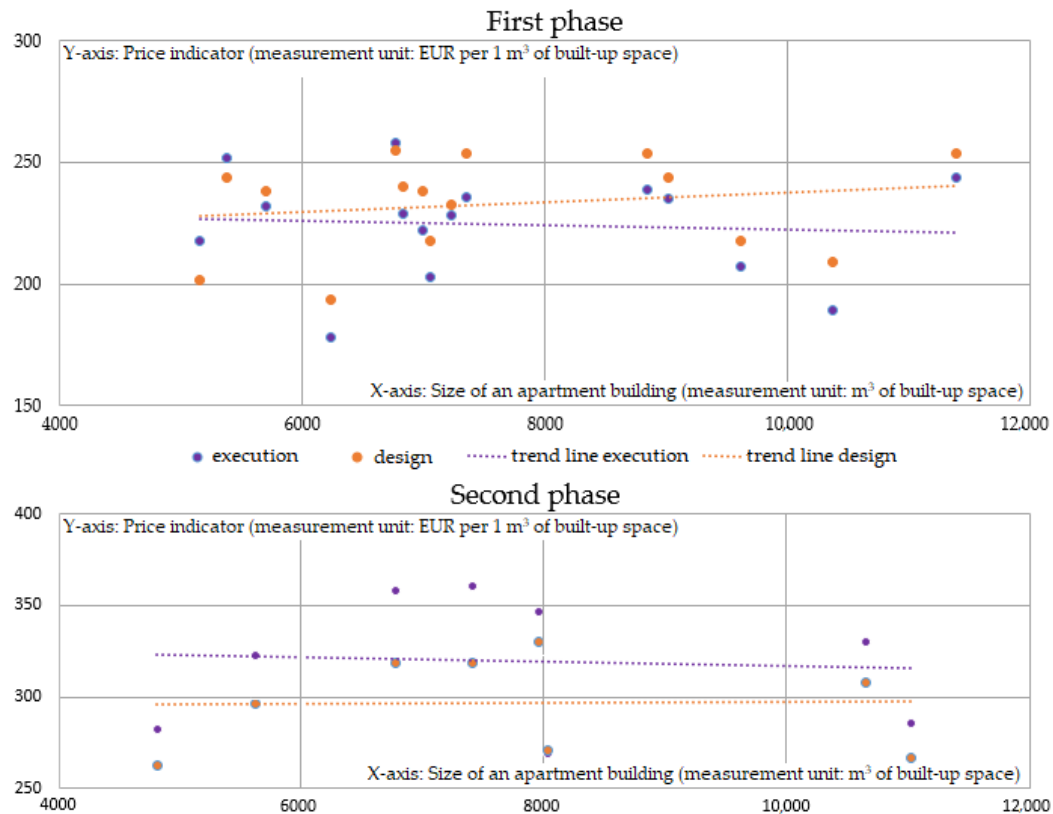


Figure 6. Dependency between the size of an apartment building and the price indicator.

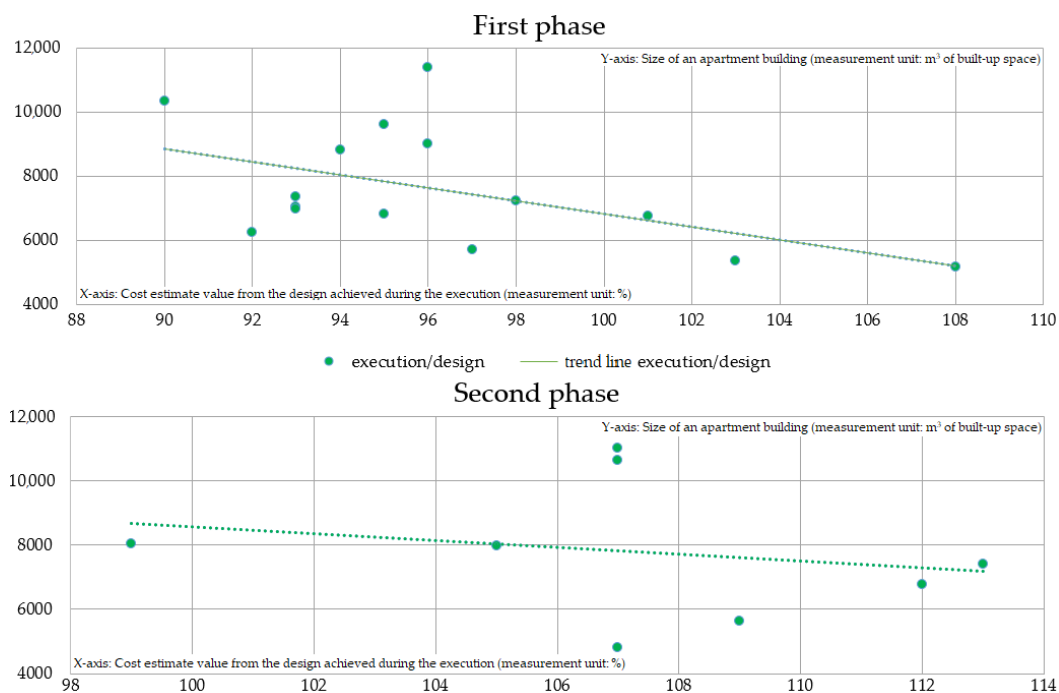


Figure 7. Dependency between the size of an apartment building and the cost estimate value from the design achieved during execution.

In comparison with the outputs of other colleagues, it can be stated that research oriented towards this area of problems is not very common. However, the available data suggest some similarity in the conclusions drawn. Precisely, this mainly applied to the outputs of the first phase, where the smaller the building was, the more accurate the cost estimation from the design stage at execution. As a rule, these publications reflected the situation on the Asian continent [9,24], where the above conclusions were still valid in recent years (2022 and 2023). In the Czech Republic, however, an increased inflation rate affected not only the construction market.

- The degree of correlation between the price indicator and time:

For both phases, a statistical dependency between these parameters could be demonstrated. It covered the annual increase in the price indicator per 1 m³ of the built-up space of apartment buildings. Therefore, a dependent degree was identified, i.e., the later the design or execution started, the more expensive it was. The obtained results can be seen in Figure 8 below.

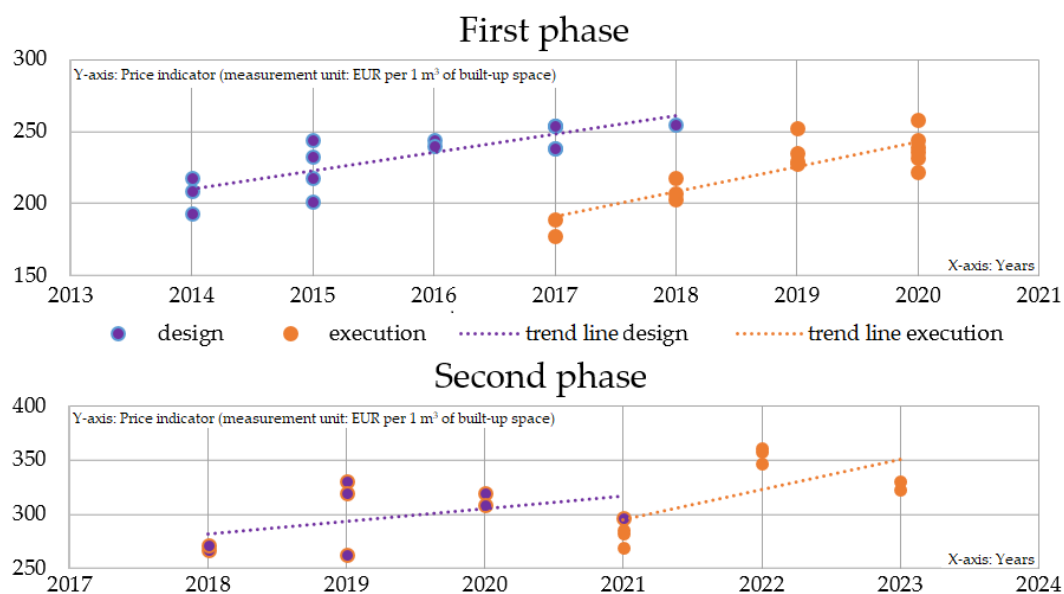


Figure 8. Dependency of the price indicator on time.

These findings are entirely consistent with the published national (CR) and European statistics for the cost sector of building production [1,2]. In recent years, according to these statistics, the most significant increase in inflation and, consequently, in prices, not only in the construction sector, was in 2022. This is in full agreement with the conclusions drawn from the obtained data by the authors of this article.

- The degree of correlation between of the price indicator and the cost estimate value from the design stage achieved during execution:

In the first phase, the dependent degree appears only for execution data, where the probability of achieving 100% (or a slight overrun) of the design cost estimate during the execution increases as the price indicator grows. The preparation stage is nearly constant when the trend line is plotted, i.e., completely uninteresting in terms of dependency. The dependent degree is also evident in the second phase, for both the design and the execution data. Specifically, as the cost indicator increases, so does the design cost estimate overrun during execution. The results achieved can be seen in Figure 9 below.

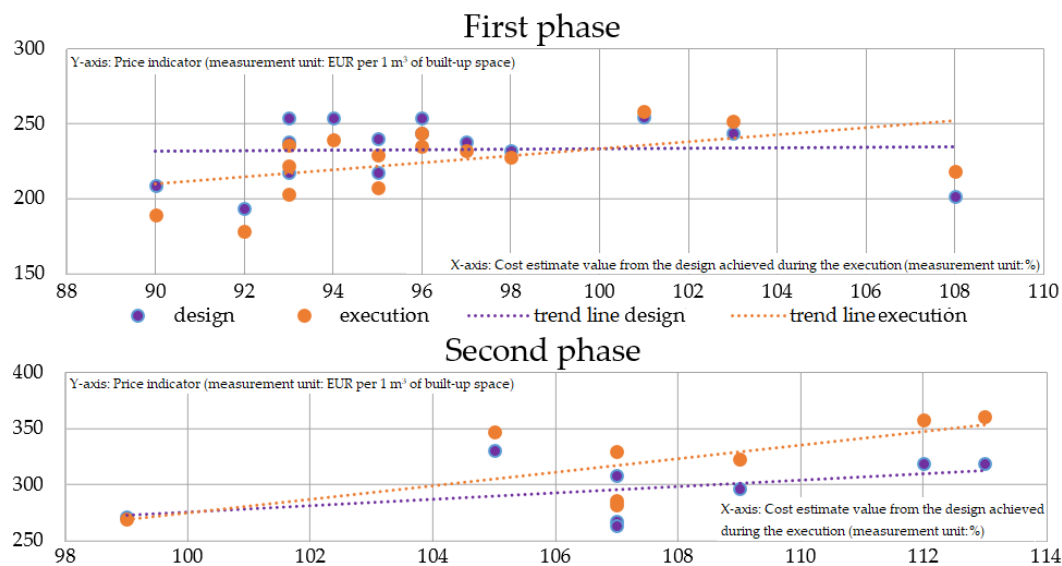


Figure 9. Dependency of the price indicator and the design cost estimate at execution.

Again, it is not possible to compare the achieved outputs with other published scientific findings directly, as the authors of this article were unable to find similarly formulated data in this context. However, the conclusions from published sources lend themselves to the interpretation that comparable results occur in other market environments. Thus, as the price indicator increases, so does the likelihood of cost overruns from the design stage during execution [11,12].

- The degree of correlation between the cost estimate value from the design stage and the costs achieved during execution over time:

In the first phase, an independent degree was identified. The trend line shows a slight correlation—the later the apartment building was designed or executed, the greater the probability of exceeding the cost estimate from the design during the execution—which, however, is statistically insignificant. In contrast, in the second phase, the degree is dependent, where there is already a demonstrable correlation between the effect of time and the resulting cost overrun from the design stage at execution. The achieved results can be seen in Figure 10 below (given the nature of the data, only the design year has been included).

The first phase was a period with a normal inflation rate and a generally “quieter” time compared to the subsequent phase. Thus, again, the presented results are consistent with economic statistics, as in the case of the dependency of the price indicator on time, elaborated above.

2. What factors and risks enter the issue of estimating costs during preparation and the costs achieved during execution?

Several factors and risks that have a significant impact on cost compliance from the design stage after execution were identified through a questionnaire. These were, in particular, an incorrectly calculated construction budget with the bill of quantities and subcontractors’ coordination within the first phase and quick growth in construction material prices and unavailability of materials in the second phase. The results of the survey are summarized in Figure 11 (below) using a matrix ranking of the respective risks for the two selected years.

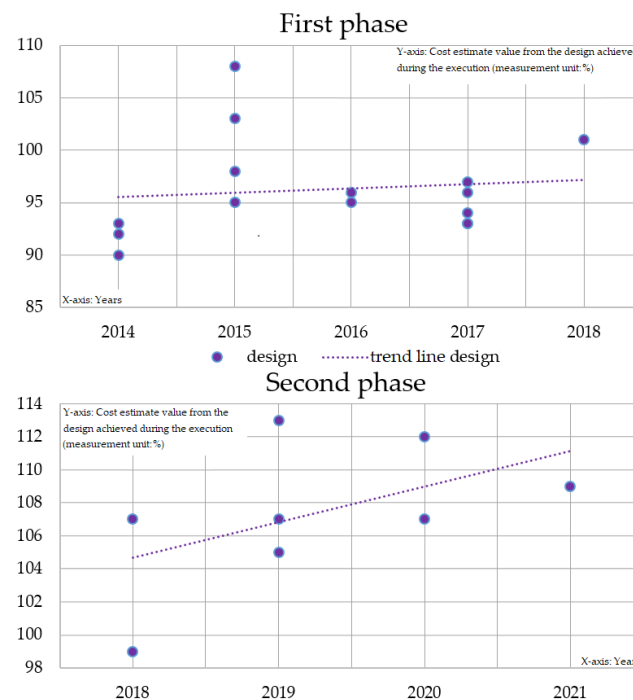


Figure 10. Dependency of the design cost estimate value at execution over time.

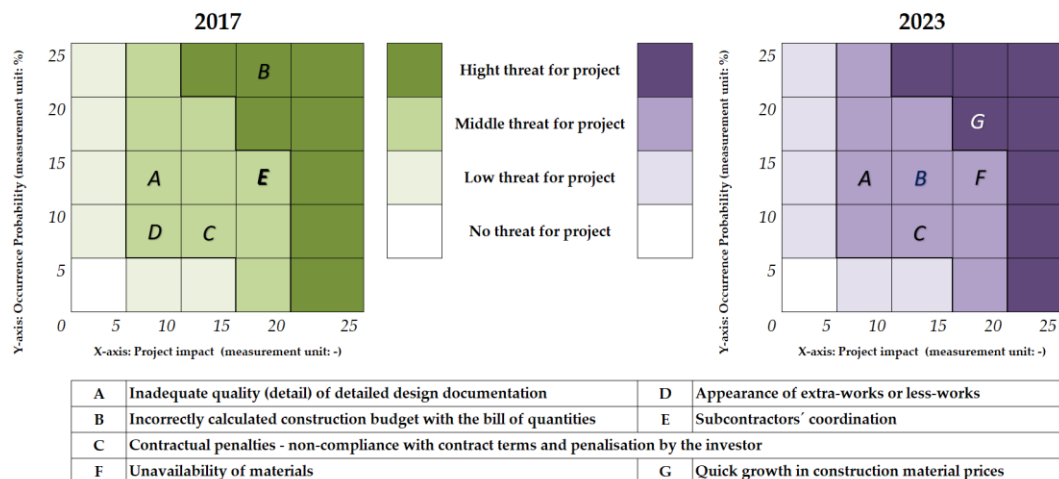


Figure 11. Matrix of risks for the two years studied (2017 and 2023).

The factors and risks associated with costs in the design and construction of apartment buildings appear relatively frequently in published research projects. Specifically, the risks of an incorrectly calculated construction budget with the bill of quantities and quick growth in construction material prices belong to the mostly commonly mentioned risks [44]. The authors of this article aimed to create two time frames to capture the variability of individual risk types and their impact rates over time for a selected segment of the construction market in the Czech Republic, where the added value of the published data is clearly evident.

3. What digitalization methods could help to refine the cost estimates from the design stage? How often are these methods applied in practice?

Building Information Management, represented by a digital building model, was identified as a digitalization method that has the potential to refine and streamline cost estimation in the design of a residential building. The BIM model was only used in two cases in the first phase and, therefore, it could not be demonstrably determined whether

it contributed to cost estimation refinement. A similar situation occurred in the second phase, but with the difference that the BIM model had been developed for one half of the apartment buildings, indicating a growing trend in its use.

In numerous professional articles, the BIM method is presented as the future of the building industry [17,18]. The contribution to cost-related issues in the building industry is also outlined in a number of research outputs, primarily in relation to the increased automation of data transfer (work efficiency) and, in particular, in the preparation of the bill of quantities for cost estimation in the design stage [25]. This is entirely consistent with the views of the authors of this article.

4. What sustainable technologies are currently being applied in the apartment building segment? Or, potentially, what are their implications for the values of price indicators and the differences between design cost estimates and execution costs?

The sustainable technologies currently used within residential buildings are primarily heat pumps, photovoltaics and heat recovery units. These technologies have only been applied to a greater extent in the second phase. In contrast, technologies for green roofs and grey water recovery rather have a minority share. The collected data imply that in the cases where sustainable technologies were incorporated, the price per 1 m³ of built-up space reached higher values than in the apartment buildings where these technologies were not used (information in Tables 2 and 3). Regarding the differences between the design and post-execution costs, given that they were applied, it was only in the second phase that the design cost estimates were often exceeded. However, the authors of this article are more inclined to associate this finding with a more dynamic and less stable price period represented by high inflation rates and uncertainty.

The outputs from other researchers mention sustainable technologies in conjunction with higher acquisition costs, as in [37]. However, in several cases, they highlight their contribution to the life cycle of a building through Life Cycle Cost (LCC) [45] and Life Cycle Assessment (LCA) [46] methods, which are not the focus of this article. As for the selection of specific technologies, in many cases, it is linked to the capabilities and standards of the respective country. The selected technologies applied in the Czech Republic are also common in many other countries.

3.3. Summarization of Results

Again, the results are summarized by phase. In the first phase, from 2017 to 2020, the authors had data from 15 apartment buildings available. This period is more stable in terms of price stability and adherence to building design predictions without significant outliers. The year-over-year inflation rate grew at a maximum of 3% in the Czech Republic, and cost compliance from the design stage reached an average of 96% and a median of 95% after the execution stage (i.e., as a rule of thumb, the cost estimate from the design stage was higher than the cost after completion). This is evidence of well-managed cost predictions over time, good work with risks and a stable market environment. The price indicator value per 1 m³ of built-up space of residential buildings reached an average annual increase of 5% during design and 9% during execution, i.e., higher than the average annual inflation rate (2%). This was probably linked to efforts to increase the profitability of the building industry, which is still financially undervalued compared to other industrial segments. The average price indicator per 1 m³ of built-up space was around EUR 233 in the design and EUR 225 after the execution, where the cost estimate from the design stage was exceeded only in three cases in the execution stage (graphically summarized in Figure 12). Unfortunately, the BIM model was only used in two cases and, therefore, it cannot be demonstrably established whether it had contributed to compliance with design cost during execution.

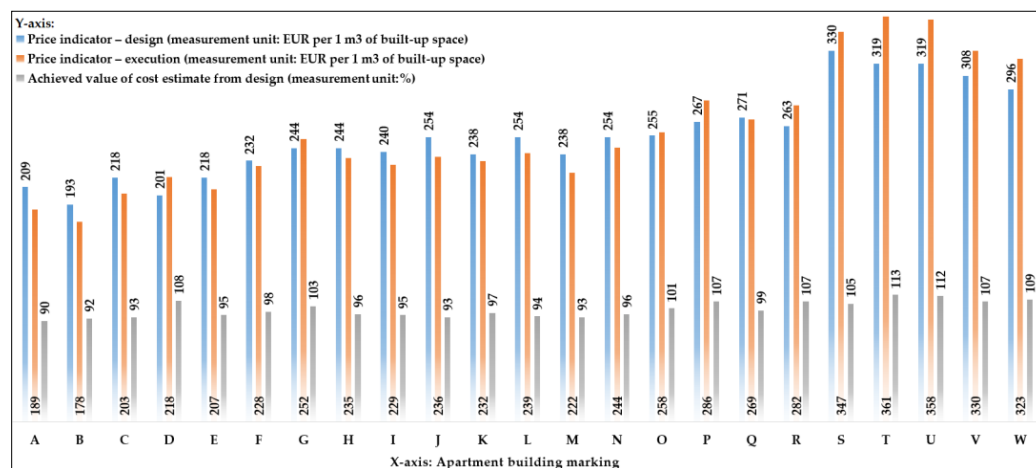


Figure 12. Evaluation of key price indicators and achieved values of cost estimate from design stage for apartment buildings.

In the second monitored period, 2021 to 2023, the authors had data from 8 apartment buildings available. This period was significantly more dynamic in relation to price stability. In addition to socio-economic aspects, the application of sustainable technologies and a higher involvement of the BIM method were also manifested there. These facts (mainly the socio-economic ones) had been reflected quite fundamentally in all the indicators according to which construction projects were evaluated within the research project. The year-over-year growth in the inflation rate climbed to a double-digit figure of 15.8% at its peak. This growth resulted in only one case where there was no cost overrun between the design cost and the execution cost. The mean and the median were the same, reaching a value of 107% (i.e., in general, the cost estimate from the design stage was lower than the execution cost). The price indicator value per 1 m³ of built-up space of the apartment buildings showed an average annual increase of 4% for the design and 11% for the execution, which is slightly higher than the average annual inflation rate increase (10%). Among potential reasons impacting these results is the price fixation performed by key subcontractors already at the contract preparation stage by the general contractor. This fact may have “protected” the contractor against even more significant differences during the subsequent execution stage as compared to the cost estimate from the design stage. The average price indicator was EUR 297 in the design stage and EUR 320 in the execution stage. The highest difference in the values of the price indicators for both phases (the whole research period) was EUR 137 for the design (i.e., a difference of 170%) and EUR 183 for the execution (i.e., a difference of 202%). As in the first phase (2017–2020 period), the second phase failed to clearly demonstrate whether BIM models had “helped” or “failed” to keep the execution cost at the design cost level. However, a BIM model was developed for a total of four construction projects, proportionally representing 1/2 of the cases in the second phase, which shows a growing trend in the application of digital technologies in practice. At the same time, this recent period has witnessed the notable incorporation of sustainable technologies in the form of heat pumps, photovoltaics, heat recovery units, etc. From the collected data, it can be deduced that the price indicator per unit of built-up space reached the highest values in the cases where sustainable technology was used. It should be pointed out that this higher occurrence of sustainable technologies is also the consequence of “green” national legislation. In the questionnaire, the respondents established a 3% threshold for the difference between the cost estimate from the design and after the execution. A total of 8 construction projects out of the 23 included in the survey “managed” to get above 103%, with 7 of them (the majority) belonging to the second phase (period of 2021–2023).

The last aspect covered in this article is the identification of the factors and risks affecting compliance with the costs from project preparation. The traditional factors and risks associated with an incorrectly calculated construction budget or poorly detailed

design documentation were complemented by the coordination of subcontractors due to their high involvement in civil engineering. Unfortunately, when choosing a suitable subcontractor for selected construction activities, the lowest price for the contracted works is still the prevailing criterium. A potential solution may be to accept higher prices that could bring high-quality subcontractors into the construction process. Long-term cooperation established with them can help to significantly reduce this risk. In contrast, the BIM method in the form of a model has the ambition to eliminate the traditional risks associated with errors in the project or with poor budgeting. The incorporation of this method into routine construction processes will enhance competitiveness and credibility in the eyes of investors, in addition to cost accuracy. Unfortunately, there is still a lack of representative samples in the Czech Republic to conduct high-quality research and confirm the hypothesis of the elimination of the above-mentioned risks. In the second phase (2021–2023), the risks associated with resources or building materials became apparent, both in terms of their availability and sudden price fluctuations that did not follow the expected development trends. Although these risks ranked high in the risk matrix, 2024 will see a calming and stabilization of the construction materials market, which will probably reduce the significance of these risks in the medium term again.

4. Conclusions

This article focuses on an issue that is undoubtedly topical in every period, i.e., how to “manage” to keep the estimated costs from the design stage of a building project at the same level during its construction. The accuracy of the cost estimate from the design itself and adherence to it during the construction process represent the ability of construction companies to handle not only pricing. Within the monitored period (2017–2023), several situations occurred (the COVID-19 Pandemic and armed conflict in Ukraine) that were difficult to predict and consider in the pricing of construction projects, not only from the perspective of Czech construction companies. It was mainly because of the above circumstances, which had a significant societal impact, that the authors decided to divide the monitored period into two phases, i.e., 2017–2020 (completed construction design from 2014) and 2021–2023 (completed construction design from 2018), so that the data obtained could be interpreted better. The respective data were obtained within a research project of the Centre for Advanced Materials and Efficient Buildings at the Czech Technical University in Prague from 23 completed apartment buildings with a built-up space of 5000 to 13,000 m³ and construction costs ranging from EUR 2.5 to 6 million located in the three largest cities of the Czech Republic. Together with data on the costs from the design and execution stages of individual apartment buildings, the respondents (representatives of 12 construction companies with an annual turnover of over EUR 40 million) provided their opinions on the risks associated with the issue. The authors of the article have incorporated numerous information obtained from public sources (Czech Statistical Office, Eurostat, etc.) into their calculations to add context to the situation prevailing at the time, mainly through selected economic indicators and indices.

Based on several years of research, the authors see the scientific novelty of the published article in several points related to apartment buildings:

- The identification of the factors and risks affecting cost differences between the design and execution stage in two time frames with their probability of occurrence and potential impacts on the construction project;
- Capturing the evolution of price indicators over the last seven years, both in terms of the design and execution;
- Creating a realistic picture of the work with costs during the execution stage by comparing them with the estimate from the design stage;
- The compilation of different types of dependencies between the cost, time and technological parameters of a building, providing an interesting and well-founded picture of the obtained data;

- Capturing the differences between the cost estimates from the design stage and the actual costs achieved during execution over time;
- The compilation of types of sustainable technologies gradually incorporated within a selected segment of the building industry, including cost implications for design and execution;
- The determination of the frequency of the use of the BIM method (especially the BIM model) and its meaningfulness, especially in cost estimation in the design stage;
- The general approach to data collection and data evaluation in cost issues in the building industry.

The authors see some limitations in the outputs of this article in several areas. The first one is the source data, which were obtained from leading construction companies in the field of residential development, but not from the whole market and only for the largest cities in the Czech Republic. The fact of covering only selected cities may affect the values of price indicators per 1 m³ of built-up space, where it can be assumed that in smaller cities, the price indicator value could be lower and, therefore, the results are not relevant for the whole of the Czech Republic. Another limitation of the outputs could be the type of selected technologies that were part of individual apartment buildings. For example, the research did not include timber frame houses, precast concrete houses, etc. This is also true of the application of selected sustainable solutions, where lower involvement was identified, particularly in the areas of green roofs and grey water (however, this is a realistic picture of the market). The final apparent limitation of the published data is the fact that the monitored period witnessed dynamic price fluctuations caused by many factors, resulting in a limited informative value in their interpretation in terms of the observation of long-term price trends in the building industry.

The authors primarily see topics for further research in three disciplines. The first area focuses on the development of relevant methods and techniques for identifying dependencies, algorithms and trends in pricing in the building industry that represent current market needs. The next area is the creation or modification of standards used to construct digital models of buildings to approximate the requirements necessary to produce cost estimates in the preparation of construction. That is, linkages to local pricing practices, usually associated with pricing databases, are used to enable as much automation as possible in the production of bills of quantities and construction budgets. The final topic is to focus research on the systematic collection of more than pricing data for sustainable technologies, which are having a great boom in residential development.

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