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Research paper

Forecasting the course of construction project management in conditions of uncertainty

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Abstract: The methodology and research results presented in the article indicate the practical possibility of conducting optimization of construction project management course. The goal of the achievement leads to the rationalization of the management of investment tasks, in which there are a series of uncertain parameterized events. The goal was achieved through many years of the author's own research, which was personally carried out on several hundred construction projects according to original methodology for assessing and forecasting the characteristic parameters of construction investments (cost and time) in conditions of uncertainty: from determinism, through probability and randomness, to fuzziness. The presented and documented achievement stands for accomplishment in project management of construction projects, where decision-making with an increasing degree of uncertainty takes place and requires the course of investment tasks that will be implemented in the future to be forecasted. In the conducted research and conclusions it was proven that construction processes should be considered as phenomena with random events and various degrees of uncertainty, to which methodology with developed modelling parameters should be used.

Keywords: construction project management, cost, fuzziness, time, randomness, risk, uncertainty

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1. Introduction

A researcher and / or decision-maker (these roles are very often combined), when forecasting the course of construction processes, makes decisions about their future condition. These decisions can be made hypothetically (using a heuristic search) or can be modelled based on previously acquired knowledge (empirical distributions of variables relevant to the real condition), and give the researcher and decision-maker a certain level of probability as to the correctness (truthfulness) of their decision. Decisions can also be undertaken as a result of the application of specific algorithms, which, as long as the taken actions are consistent with the algorithms developed for the given procedures, ensure certain effects.

A researcher operates in a situation of **uncertainty**. The state can be treated as a continuum with two borderline situations:

– **Determinism** – a situation of empirical knowledge, which results from research and empirically confirmed states of affairs after the application of specific algorithms. All that is needed to be done in this situation is to follow the procedures. The level of uncertainty regarding the effects of made decisions and taken actions is **minimized**;
– **Randomness** – a situation in which there is no knowledge about the actual condition, and which allows for the rationalization of the premises for assessing the past condition, or for the building of models of future actions. Each effect appears to be the result of chance, as the lack of knowledge does not allow for any prediction. The only thing that can be referred to in this situation is probability without distributions.

However, from the defined research goal, the points that describe model situations, which are located between two borderline situations, are crucial:

– **Probability based on unambiguous distributions**, which were determined on the basis of risk measurements made on strict and unambiguous scales, is the closest to a situation with a deterministic character.
– The situation closest to randomness is an **ambiguous and uncertain situation**. Here, as was the case in the previous situation, the researcher makes decisions based on empirical distributions of specific features. Their values are determined not on the quantitative, but on the qualitative (ordinal) level of measurements.

The conducted research involves the supplementation of these scales with situations that are based on **fuzzy distributions**. In this way, a model class of events on the scale of decision uncertainty was created as a class of ambiguous situations. Using the logic of fuzzy sets, as well as transformations that are based on this logic, membership functions were formulated. They allow for a precise (in quantitative categories) determination of the value of the belonging of a given object (phenomena, features, classes, events) to a set that is defined by an unclear concept in terms of meaning (e.g. average wear or low cost).

In reality, a project manager makes a series (and not one) of interference decisions that combine the specifics resulting from belonging to different classes that are described on the decision uncertainty scale. That is why the practical application resulting from the research presented in the article comes down to the modelling of various combinations of research and decision situations.

2. Literature survey

The author's published papers on construction process engineering shows that applied techniques have been used to generate cash flows in construction projects [1–5], including the logic of fuzzy sets and artificial neural networks [6, 7], decision models, deterministic and stochastic models, models requiring simulation, and models that take into account uncertainty on different levels of possible risk [8–10].

The correct identification of investment risk, as well as the proper planning and reliable control of the course of construction projects, are essential for their rational management. Unfortunately, there is a small probability that an investment task will run as planned with regards to all its aspects. Small deviations between the plan and reality are seen as standard and usually do not interfere with meeting the budget and deadline. However, larger differences may hamper the achievement of the investment target and require ongoing adjustments in order to maintain the "Kerzner triangle" optimum when managing investment tasks [11]. The problem of exceeding the planned budget, or not meeting planned deadlines, is common in all countries [12–14]. The simplest S-curve planning methods assume that the data used to generate the curves are known and deterministic, and they do not take into account possible risks and uncertainties. However, there are methods that incorporate the use of stochastic curves in probabilistic monitoring and project forecasting. These methods are alternatives to deterministic curves and traditional forecasting methods. To generate stochastic cost curves, for example, the simulation method is used, which is based on defining the variability of the duration and cost of individual activities in the project [15].

A stochastic approach to cash flow management, which takes into account the uncertainty of duration and costs at different stages of the project lifecycle, is also applied [16]. To this end, various methods, tools and techniques are being developed for the planning and monitoring of construction projects. For example, fuzzy set theory [17] is used to assess the impact of quantitative and qualitative factors on the assessment of the demand for working capital in construction projects. As part of the proposed research methods that use artificial intelligence, apart from fuzzy logic, k-means clustering, genetic algorithms and artificial neural networks [18, 19] are also used for cash flow monitoring.

When planning the costs of construction projects during the life cycle of a building object, there are also models that take into account cost risks [20] and the risks associated with construction works and the analyses of situations in which events may occur randomly and may change the duration or cost of the project, or even reduce its quality [21, 22]. The probabilistic approach to the estimation of cumulative costs is also used in the concept of developing the envelope of cost curves, in which two curves are determined: the upper curve representing the earliest times, and the lower curve representing the latest times. The curves are obtained on the basis of the parameters that were calculated for the project. They also take into account the earliest possible start and end dates, and the latest start and end dates of the project, as well as potential delays that may occur during the performed works in normal and emergency time [23]. Valuable works about the construction investment process with the fuzzy phase indicate the practical application of uncertain and subjective events in the modelling of construction projects [24–27].

In the literature, many works presenting the effective application of the Earned Value Method (EVM) in real construction projects can be found, e.g. the construction of three airports in Belgium [28, 29], the construction of a logistics centre in South Korea [30], the construction of railway infrastructure on the peninsula in Malaysia [31] and variety of construction project costs in Poland [32–35].

A thorough analysis of publications led to the conclusion that the previously proposed models of forecasted S-curves usually differ from reality and are too complicated. Therefore, they are not practical when planning and managing construction projects. This is due to the fact that cumulative cost curves have different courses, which are not always consistent with those described in literature [36, 37].

3. Methods and models

3.1. Research approach

A real challenge is the analysis of past states, with their effects being seen in the present, as well as the current modelling of continuous processes, the effect of which will be visible in the future. When using two-valued logic, where an arbitrary conclusion results from the premise, the decision is determined by the inference model. And when such logic is insufficient, it has been noticed that decisions cease to be deterministic, and they become multivariate. Actions are also undertaken in a multi-variant way, and they assume the tracking of circumstances and a possible change during the implementation of the decision. There is no doubt that this real situation is more complicated, and therefore requires a more complex decision management process.

The engineering and managerial challenge, defined in such a way in conditions of uncertainty, has been the subject of my scientific research and professional interests for over 30 years. This approach can be illustrated in the following coordinate system shown in the Figure 1.

The following model parameters are marked on the ordinate axis:

– the number of stages of decision making, which determine:
  - one step – the static approach;
  - two and many steps – the dynamic approach;
– the propagating degree of uncertainty, marked on the ordinate axis, is defined as follows:
  - certainty: all information describing the issue of decision-making is of a cause and effect nature, i.e. deterministic, which means that it is known exactly what the options for making decisions are, and what a given choice gives regarding some usefulness (e.g. value analysis); in this case, making decisions comes down to the direct maximization of the utility function;
  - risk: information describing the decision-making issue is probabilistic, i.e. appropriate probability distributions are determinable; in this case, making decisions comes down to maximizing the expected value of the utility function and quantifying the risk and its minimization;

- randomness: even the probabilities are not known; making decisions usually comes down to applying a minimax strategy in order to ensure the highest utility value in the most unfavourable conditions;
- fuzziness: uncertainty not only concerns the occurrence of a certain event, but also its meaning in general, which can no longer be described using probabilistic methods; of course, further extensions are possible, which involve e.g. adding risk to fuzziness.

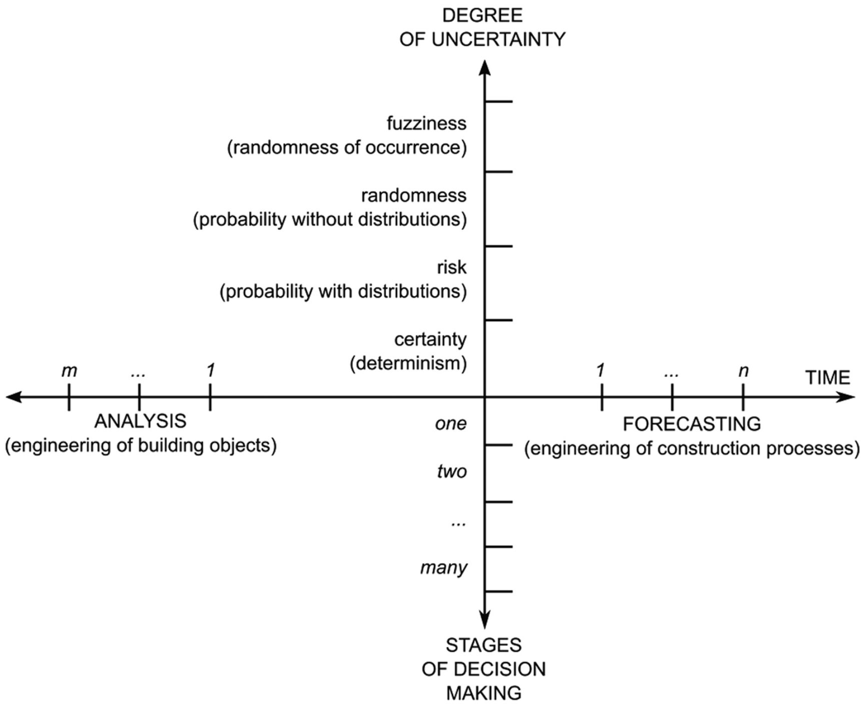

Fig. 1. Scheme of making management decisions under conditions of uncertainty [own elaboration]

Unfortunately, not all the forms of tasks have a consistent theory and relatively constructive results. In general, it can be said that the further the experts move along individual axes, the less elaborated the individual issues are.

3.2. Research sample

The data for the development of my own research methodology is the result of my own experience and professional work, which consists in providing Bank Investment Supervision (BIS) services (in the years 2006–2020) for banks granting investment loans for non-public procurement. Over the period of 15 years, together with a BIS team, I collected and processed cost data by conducting monthly and direct technical and financial inspections at construction sites of implemented investments. The measurement of the cost and budget of investment tasks was documented in 536 BIS reports: preliminary reports

(PR), monthly reports (MR), and final reports (FR). The research covers various construction projects in 8 typologically and quantitatively diverse research samples: collective residence buildings, office buildings, hotels, retail parks, logistics centres, health centres, airports and industrial plant. The summary of the number of cumulative cost measurements in the reports is presented in Table 1.

Table 1. The number of cumulative cost measurements in BIS reports

Group/construction sector	Number	Time of measurements	PR	MR	FR
A. Collective residence buildings	14	2006–2020	14	169	6
B. Office buildings	4	2008–2020	4	55	
C. Hotels	9	2013–2020	9	93	8
D. Retail and service parks	8	2008–2018	8	97	8
E. Logistics centers	2	2017–2020	2	8	2
F. Health centers	1	2011–2012	1	10	1
G. Airports	1	2011–2015	1	35	
H. Manufacturing plants	1	2018–2019	1	4	1
Total number of reports: PR–MR–FR			40	471	26
TOTAL NUMBER OF REPORTS			536		

Such data was collected and processed during the last 16 years by conducting monthly direct technical and financial inspections at construction sites of implemented investments. The collected data was the result of measurements of the current state of the amounts of executed works/the execution of construction works. The increasing values ??of the amounts of executed construction works on the construction site constituted the cumulative cost, which when specified cyclically and consistently by the same authors with an auditing approach to the measurement, determined the course of the S-curve. This S-curve corresponded to the monitored and controlled construction investment. The measured number of construction works performed, and the data on the completed construction projects, which was processed in accordance with the standardized technical and financial methodology, should be considered as reliable, consistent and legible. They can be used to distinguish typological research samples for investments of a similar profile. Construction cost measurements documented in BIS reports, the number of which is greater than 100, can additionally be extrapolated to homogeneous populations that correspond to, for example, construction sectors.

3.3. Research method

A clear picture of the adopted research methods are graphs of cumulative cost curves – planned, current and earned in the areas of uncertainty – Figure 2. It was assumed that all 3 S-curves can be determined in a probabilistic approach, which has known distributions of variables until the moment of the measurement of cumulative costs in a construction project. After that, the current cost curve is random and without an unequivocal probability distribution. In the final phase of uncertainty of the cost overrun, it should be described using a fuzzy approach.

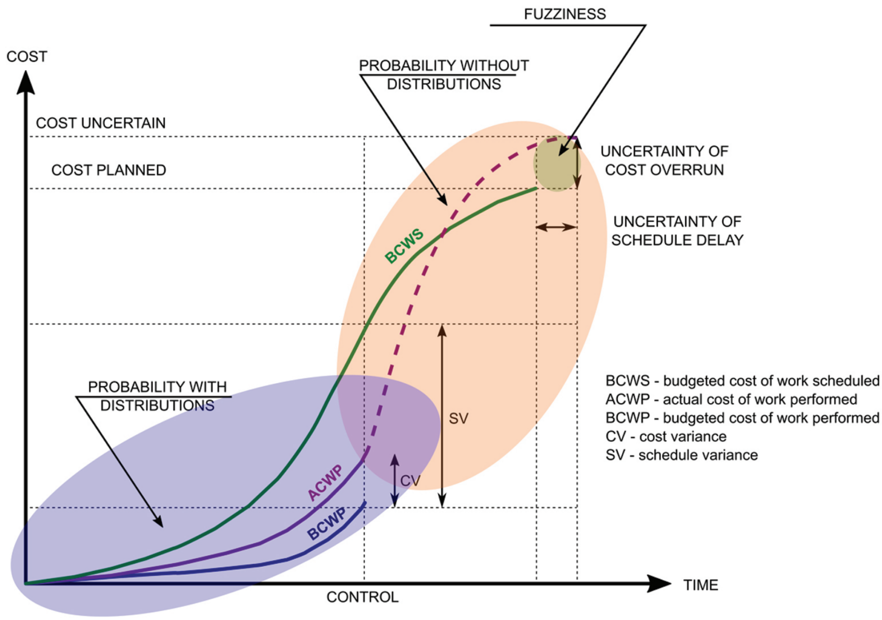

Fig. 2. Curves of planned, actual and earned costs in the areas of uncertainty [own elaboration]

The research approach in the purposefully prepared research sample involves a deterministic, random and fuzzy projection of the course of various construction projects in terms of comparing the planned, incurred and actual earned costs, as well as indicating the basic causes for cost deviations from the earned values, i.e. actually contracted and performed on the construction site. Only such a diversified approach enables the course of construction processes under conditions of uncertainty, which are the subject of my own research, to be reliably forecasted.

3.4. Modelling in conditions of uncertainty

The purpose of modelling the first part of the author's own research is to determine (in a measurable manner) the important parameters of the investment task that significantly affect its subsequent cumulative cost.

The purpose of modelling the second part of the author's own research is to monitor and project the course of various construction projects in terms of the planned, incurred and actual earned costs, and also to identify the basic causes for cost deviations from the earned value, i.e. actually performed on a construction site.

The identification of construction risk in construction projects, the determination of the strength of its impact, the possibility of its occurrence, its significance, as well as its monitoring and elimination with preventive measures, cannot be overestimated during the proper management of the investment process in the construction industry. Risks of the investment process, which have the greatest impact and the highest probability of occurrence, and which are therefore of significant importance in the construction project, were identified. The investment risk management strategies that can have the greatest impact on the increase in the cost of the investment process were identified. The correlation of the impact of risk on the parameters of the feasibility of investment tasks (with the probability of these risks) was determined in a measurable way using a point two-series correlation coefficient of various types of characteristics. It should also be remembered that there is uncertainty as to the occurrence of some areas of construction risks, and therefore their nature lies closer to fuzziness than probability that has a better developed mathematical apparatus for the modelling of investment processes.

Another aspect of modelling this part of the investment process, which has a significant impact on the cost of the project, is the issue of the occurrence of unforeseen (replacement and additional) construction works, i.e. those not included in the budget of the investment task. The occurrence of these undesirable and unforeseen events starts during the tendering procedure and the shaping of the form of the contract for the performance of construction works between the contracting authority and the contractor, regardless of whether the project is financed from private funds or whether it is a public procurement. The well-known and commonly used patterns of engineering contracts, such as FIDIC, VOB, NEC, and JCT provide many systems of financing and settling construction works that are the subject of the contract. From the point of view of the possibility of the occurrence of unforeseen works, the various forms of contracts can be divided into two groups:

– reimbursable contracts, which from the very beginning assume the occurrence of additional and replacement works that are the subject of as-built settlements between the contracting authority and the contractor; here – the random event, described as unexpected construction work, is of a random nature and occurs with a specific, determinable probability;

– fixed fee contracts, according to which the need to perform replacement and additional works may arise only at the stage of implementing investments; here – the random event, described as unforeseen construction work, is of a fuzzy nature and its occurrence is linearly determined by the membership function to the set of fuzzy events, which are identical to the unforeseen events.

Identification of the causes of the emergence of the need to perform works that are not foreseen at the investment design stage would be a fundamental premise for improving the known models of the rational management of a construction project, as well as for minimizing the risk of the occurrence of replacement and additional works. The research problem defined in this way is a big challenge, and it is worth associating it in the future with the modelling of the course of costs in the engineering of construction processes under conditions of uncertainty.

Afterwards, a knowledge base was built in the form of tables that are prepared for the value and cumulative analysis of the monthly cost and time of 40 construction projects from 8 different investment sectors. On their basis, charts of planned / cost estimate, invoiced / incurred, and actual / earned values of the cumulated costs of the examined construction projects were prepared. The levels of the cumulative amounts of the executed construction works were determined using the S-curve. The course of the S-curves was plotted on the basis of the cumulative values of the amounts of executed construction works, which constitute the cumulative cost that was systematically determined by the same authors from the BIS team. Selected graphs of the cumulative costs of the BCWS (initially planned), ACWP (incurred/paid), and BCWP (actually earned) of the EVM curves in homogeneous groups, and also the BCWP graphs in a diversified group, were presented.

Calculations conducted in accordance with the methodology of the EVM enabled the actual earned costs of individual investment tasks to be assessed. Analogies were observed in the shaping of the trend of the cumulative cash flow curves, both within the same groups of buildings, and also between them. The areas of the S-curve of the correct cost planning for individual analysed groups of investment tasks, and the course of the curve with the best adjustment to the trend, were determined. The designated areas between the analysed curves show the range for the project budget and its cost flows. If the curve runs outside the area of ??a good cost estimate during the comparison of the actual curve of the task with the planned one, advance corrective actions should be taken and a recovery plan should be implemented. On the basis of the obtained data set, it was possible to determine the best adjustment of the S-curve to the trend function. As a measure of the adjustment of the trend function to the actual values, the correlation coefficient R and the coefficient of determination R^2 (which is a measure of the extent to which the model fits to empirical data) were used.

4. Conclusions

Completion of this stage of the research in the field of the engineering of construction processes under conditions of uncertainty prompts me to present a concise recapitulation and the following conclusions of a practical nature.

In the deterministic and risk part – I:

- calculations made in accordance with the methodology of the EVM allow for the assessment of the actual costs of individual investment tasks; there are analogies in the trend of cumulative cash flow curves, both within the same groups of construction objects and between them [1, 2, 4];
- correct planning of cost flows has a fundamental impact on both the liquidity of construction companies and the achievement of success in the implementation of construction projects; a helpful tool for planning, monitoring and controlling construction projects is the S-curve [3, 5];
- S-curves with high accuracy fit into the 6th degree polynomial with values of determination and correlation coefficients close to one [36];

- for the area of the S-curve of the planned costs, the 6th degree polynomial describes the course of the actual cost curve at the correlation level close to 1 and with an accuracy of over 95% [36];
- planned costs resulting from the planned work and expenditure schedule significantly differ from the actual costs incurred during the implementation; the actual cost of implementation is 2–19% higher than planned [37];
- in the second stage of the implementation of works, the costs are generated at a much faster pace than planned; for half of the planned duration of works, the planned work and expenditure advancement is approx. 24%, while for the real duration, the actual advancement is approx. 28% [37];
- actual costs, from 50% to up to 80% of work and expenditure advancement, are generated at a much faster pace than which results from the Investor's work and expenditure schedule [37];
- the risks of the investment process identified above have a significant impact (0.65 on average) on the success of a construction project [8, 9]:
  - most risks occur with the probability of not exceeding 0.4;
  - the risks with the greatest impact are less likely to occur, and those with the lowest impact are more likely to occur; such a favourable lack of correlation between these two parameters indicates a moderate level of significance of the risks of the investment process, which does not exceed 1/3 of the possible significance in the "risk monitoring" strategy;
  - these risks are therefore "manageable", and thorough monitoring of the Bank Investment Supervision allows for the minimizing of the error of improper financing of investment tasks;
- the results of the study of the relationship in risk (impact – probability), using the two-order correlation coefficient of various types of traits, indicate that [9, 10]:
  - the direction of the relationship is right-handed (positive) for all the 8 analysed construction risks, but the strength of the correlation between the effect of the existing risk and the probability of its occurrence shows a significant spread;
  - the correlation trend is particularly clear and significant when it exceeds the value of 0.5, which is the case for more measurable and quantifiable risk areas in a construction project, such as the investment schedule, task budget, technical design and health and safety regulations.

In the probabilistic and fuzzy part – II:

- when estimating the probability of the occurrence of replacement or additional construction works in a construction project, apart from immeasurable (qualitative) criteria, measurable (quantitative) criteria, which are expressed in the analysis of the flow of financial resources during the implementation of the construction project, are used [7];
- in as-built engineering contracts, a random event, defined as an unforeseen construction work, has a random nature and occurs with a certain probability; in turn, in fixed fee contracts, such a random event is fuzzy and its occurrence is determined linearly by the membership function to the set of fuzzy events, which are identical to unforeseen events [6];

– the striving for a quantitative approach to criteria that are inherently qualitative, and the desire to determine the relations between them, led to the issue that is considered in the categories of fuzzy sets as a derivative of the probabilistic approach; their properties enable replacement and additional construction works to be described within an unambiguous quantitative aspect [6];
– regardless of the nature of the predictability of the described phenomenon, the reasons for the occurrence of additional and replacement (unforeseen) construction works are errors – intentional or unintentional [7];
– the group of causal errors and the group of unpredictable works that cause these errors can be marked as two fuzzy sets, which remain in a fuzzy relation with each other, and which can be described by fuzzy equations and the matrix of fuzzy relations [6];
– all the fuzzy relations that are determined as unforeseen works, which correspond to the specified causal errors in 4 groups, and to 10 typical additional activities in investment tasks, can be calculated and presented in the fuzzy relation matrix [6]:
  • about ¾ out of 250 relationships are connected with each other, and half of them indicate strong fuzzy relational relationships with a value of above 0.5;
  • only one category of causal errors (a defective business plan of the investment and an underestimated budget of the investment task) shows a complete and strong impact on all unforeseen investment activities in the analysed construction projects;
  • the height of the examined fuzzy relations reaches normal values (full as is the case in deterministic events), which are equal to 1 in as much as 10% of the determined relations;
– 80% of investment tasks end with the cost being exceeded, but this is not known until about half of the duration of the project; it seems advisable to deeply study the uncertainty of the cost overrun with the fuzzy phase [6].

5. Summary and discussion

The methodology and research results presented in the article are the result of analytical and synthetic works, which lead to model solutions concerning the aspects of feasibility, schedule, risk, contracting, and the course of cumulative costs in various construction projects. In studies of the engineering of construction processes under conditions of uncertainty, an attempt was made to analyse the subject of research using a deterministic approach, and where it was difficult or doubtful, a probabilistic and fuzzy approach. It was proved that full determinism is limited to the measurable values of the incurred (earned and paid) costs, while in terms of uncertainty – where the statistical distribution is difficult to determine and where it is ambiguous – an effective research tool is the quantification of risk towards the determination of its significance and the calculation of fuzzy sets for unforeseen construction works.

To sum up, the research achievement presented in the article is the cost optimization of construction processes under conditions of uncertainty, which leads to the following 7 new original achievements:

- evaluation of the real/actual earned costs of investment tasks, the trend of the cumulative cash flow curves of which can be estimated with a high degree of adjustment when forecasting a construction process;
- determination of the area of the S-curve of the planned costs using the 6th degree polynomial, which indicates the area of expected costs in a construction project and the estimated values of their deviations;
- determination of the range of actual investment costs, which – from 50% up to 80% of material and financial advancement – are generated at a much faster pace than which results from pre-investment planning;
- demonstration of the fact that investment risks are "manageable", because those with the highest impact occur with the lowest probability, and those with the lowest impact are more likely to occur; this in turn indicates a moderate significance level (1/3) of risks in a construction process;
- proof that in as-built engineering contracts a random event, which is defined as unexpected construction work, is random and occurs with a certain probability; in lump sum contracts, such a random event is fuzzy, and its occurrence is determined linearly by the membership function, which specifies the degree of belonging to the set of fuzzy events that are identical to unforeseen events;
- identification of causal errors and a group of unforeseen works as two fuzzy sets with an uncertain degree of occurrence, in which only a poorly constructed business investment plan and an underestimated investment project budget show a complete and strong impact on all the unforeseen investment activities in the analysed construction projects;
- calculating that 80% of investment tasks end with cost being exceeded, but this is not known until about half of the duration of the project; It seems advisable to study in detail the uncertainty of the cost overrun with the fuzzy phase.

Thus, research and analysis are quite naturally divided into two parts (probability and fuzziness) in terms of uncertainty, and they cover the following novel effects:

- modelling the parameters of replacement and additional construction works as random and fuzzy events; developing a methodology for the quantifying approach to the replacement and additional construction works in the categories of fuzzy sets as a derivative of the probabilistic approach; checking whether in engineering contracts, which were accounted as built, a random event defined as unexpected construction work has a random nature, and whether it occurs with a certain probability; checking whether such a random event in fixed fee contracts is fuzzy and whether its occurrence is linearly determined by the membership function to the set of fuzzy/unforeseen events; calculating how many investment tasks in the analysed research sample end in the cost being overrun, and when and under what conditions of uncertainty this exceeding occurs as a random event and as a fuzzy event;
- performing the correlation of fuzziness and randomness in unforeseen construction works; determining the causes for the occurrence of additional and replacement construction works as intentional and unintentional investment errors; determining the relationship between causes (investment errors) and effects (unforeseen works) modelled as fuzzy relations; building a matrix of fuzzy relations (defined in this way) and calculating their range, domain and height as numerical, measurable values.

References

[1] J. Konior, "Monitoring of construction projects feasibility by Bank Investment Supervision Approach", *Civil Engineering and Architecture*, vol. 7, no. 1, pp. 31–35, 2019, doi: 10.13189/cea.2019.070105.

[2] J. Konior, "Feasibility study of construction project in compliance with Bank Investment Supervision requirements", *Journal of Civil Engineering and Architecture*, vol. 12, pp. 831–837, 218, doi: 10.17265/1934-7359/2018.12.001.

[3] J. Konior, "Determining cost and time performance indexes for diversified investment tasks", *Buildings*, vol. 12, no. 8, 2022, doi: 10.3390/buildings12081198.

[4] J. Konior and M. Szóstak, "Methodology of planning the course of the cumulative cost curve in construction projects", *Sustainability*, vol. 12, no. 6, 2020, doi: 10.3390/SU12062347.

[5] J. Konior and M. Szóstak, "The S-curve as a tool for planning and controlling of construction process-case study", *Applied Sciences*, vol. 10, no. 6, 2020, doi: 10.3390/app10062071.

[6] J. Konior, "Random and fuzzy measure of unpredictable construction works", *Archives of Civil Engineering*, vol. 61, no. 3, pp. 75–84, 2015, doi: 10.1515/ace-2015-0026.

[7] J. Konior, "Fuzziness over randomness in unforeseen works of construction projects", *Civil Engineering and Architecture*, vol. 7, no. 2, pp. 42–48, 2019, doi: 10.13189/cea.2019.070202.

[8] J. Konior, "Enterprise's risk assessment of complex construction projects", *Archives of Civil Engineering*, vol. 61, no. 3, pp. 63–74, 2016, doi: 10.1515/ace-2015-0025.

[9] J. Konior, "Mitigation of correlated risk in construction projects", *Civil Engineering and Architecture*, vol. 7, no. 1, pp. 17–22, 2019, doi: 10.13189/cea.2019.070103.

[10] J. Konior, "Significance risks evaluation of commercial construction projects", *Archives of Civil Engineering*, vol. 65, no. 2, pp. 19–33, 2019, doi: 10.2478/ace-2019-0016.

[11] S. Al-Jibouri, "Monitoring systems and their effectiveness for project cost control in construction", *International Journal of Project Management*, vol. 21, pp. 145–154, 2003.

[12] S. Gardezi, I. Manarvi, and S. Gardezi, "Time extension factors in construction industry of Pakistan", *Procedia Engineering*, vol. 77, pp. 196–204, 2014, doi: 10.1016/j.proeng.2014.07.022.

[13] S. Makesh and M. Mathivanan, "Analysis on causes of delay in building construction", *International Journal of Innovative Technology and Exploring Engineering*, vol. 8, no. 7, pp. 335–341, 2019.

[14] T. Gebrehiwet and H. Luo, "Analysis of delay impact on construction project based on RII and correlation coefficient: empirical study", *Procedia Engineering*, vol. 196, pp. 366–374, 2017, doi: 10.1016/j.proeng.2017.07.212.

[15] G. Barraza, W. Back, and F. Mata, "Probabilistic forecasting of project performance using stochastic S curves", *Journal of Construction Engineering and Management*, vol. 130, no. 1, pp. 25–32, 2004, doi: 10.1061/(ASCE) 0733-9364(2004)130:1(25).

[16] J. Yao, M. Chen, and H. Lu, "A fuzzy stochastic single-period model for cash management", *European Journal of Operational Research*, vol. 170, no. 1, pp. 72–90, 2006, doi: 10.1016/j.ejor.2004.06.017.

[17] V. Kumar, A. Hanna, and T. Adams, "Assessment of working capital requirements by fuzzy set theory", *Engineering, Construction and Architectural Management*, vol. 7, pp. 93–103, 2000.

[18] M. Cheng and A. Roy, "Evolutionary fuzzy decision model for cash flow prediction using time-dependent support vector machines", *International Journal of Project Management*, vol. 29, no. 1, pp. 56–65, 2011, doi: 10.1016/j.ijproman.2010.01.004.

[19] M. Cheng, H. Tsai, and C. Liu, "Artificial intelligence approaches to achieve strategic control over project cash flows", *Automation in Construction*, vol. 18, no. 4, pp. 386–393, 2009, doi: 10.1016/j.autcon.2008.10.005.

[20] A. Leśniak and K. Zima, "Cost calculation of construction projects including sustainability factors using the case based reasoning (CBR) method", *Sustainability*, vol. 10, no. 5, 2018, doi: 10.3390/su10051608.

[21] T. Kasprowicz, "Quantitative assessment of construction risk", *Archives of Civil Engineering*, vol. 63, no. 2, pp. 55–62, 2017, doi: 10.1515/ace-2017-0016.

[22] T. Kasprowicz, "Quantitative identification of construction risk", *Archives of Civil Engineering*, vol. 63, no. 1, pp. 63–75, 2017, doi: 10.1515/ace-2017-0005.

[23] J. Cristóbal, "The S-curve envelope as a tool for monitoring and control of projects", *Procedia Computer Science*, vol. 121, pp. 756–761, 2017, doi: 10.1016/J.PROCS.2017.11.097.
[24] N. Ibadov, "Fuzzy estimation of Activities Duration in Construction Projects", *Archives of Civil Engineering*, vol. 61, no. 2, pp. 23–34, 2015, doi: 10.1515/ace-2015-0012.
[25] N. Ibadov, "The alternative net model with the fuzzy decision node for the construction projects planning", *Archives of Civil Engineering*, vol. 64, no. 2, pp. 3–20, 2018, doi: 10.2478/ace-2018-0013.
[26] N. Ibadov and J. Kulejewski, "Construction projects planning using network model with the fuzzy decision node", *International Journal of Environmental Science and Technology*, vol. 16, no. 8, pp. 4347–4354, 2019, doi: 10.1007/s13762-019-02259-w.
[27] N. Ibadov and J. Kulejewski, "The assessment of construction project risks with the use of fuzzy sets theory", *Technical Transactions*, vol. 1-B, pp.175–182, 2014.
[28] S. Vandevoorde and M. Vanhoucke, "A comparison of different project duration forecasting methods using earned value metrics", *International Journal of Project Management*, vol. 24, no. 4, pp. 289–302, 2006, doi: 10.1016/j.ijproman.2005.10.004.
[29] M. Vanhoucke and S. Vandevoorde, "A simulation and evaluation of earned value metrics to forecast the project duration", *Journal of the Operational Research Society*, vol. 58, no. 10, pp. 1361–1374, 2007, doi: 10.1057/palgrave.jors.2602296.
[30] M. Khamidi, W. Ali, and A. Idrus, "Application of earned value management system on an infrastructure project : A Malaysian case study", *International Conference on Management Science & Engineering*, vol. 8, pp. 1–5, 2011.
[31] O. Kwon, S. Kim, J. Paek, and S. Eom "Application of earned value in the Korean construction industry", *Journal of Asian Architecture and Building Engineering*, vol. 7, pp. 69–76, 2008.
[32] M. Połoński and P. Komendarek, "Earned value method for operational cost control of civil structure", *Metody Ilościowe w Badaniach Ekonomicznych*, vol. 12, pp. 279–290, 2011.
[33] E. Kozień, "Application of approximation technique to on-line updating of the actual cost curve in the earned value method", *Czasopismo Techniczne*, vol. 9, pp. 181–195, 2017, doi: 10.4467/2353737XCT.17.158.7170.
[34] A. Leśniak, D. Kubek, E. Plebankiewicz, K. Zima, and S. Belniak, "Fuzzy AHP application for supporting contractors' bidding decision", *Symmetry*, vol. 10, no. 11, art. no. 642, 2018, doi: 10.3390/sym10110642.
[35] A. Leśniak and E. Plebankiewicz, "Modeling the decision-making process concerning participation in construction bidding", *Journal of Management in Engineering*, vol. 31, no. 2, 2015, doi: 10.1061/(ASCE)ME.1943-5479.0000237.
[36] J. Konior and M. Szóstak, "Course of planned, actual and earned cost curves of diverse construction investments", *International Journal of Construction Management*, vol. 23, no. 5, pp. 1–13, 2023, doi: 10.1080/15623599.2021.1942769.
[37] M. Szóstak, "Planning the time and cost of implementing construction projects using an example of residential buildings", *Archives of Civil Engineering*, vol. 67, no. 4, pp. 243–259, 2021, doi: 10.24425/ace.2021.138497.

Prognozowanie przebiegu przedsięwzięć budowlanych w warunkach niepewności

Słowa kluczowe: przedsięwzięcie budowlane, koszt, przypadkowość, rozmytość, niepewność

Streszczenie:

Metodyka i wyniki badań zaprezentowane w artykule wskazują na praktyczną możliwość optymalizacji kosztowej przebiegu przedsięwzięć budowlanych. Cel osiągnięcia prowadzi do racjonalizacji zarządzania zadań inwestycyjnych, w których występują sparametryzowane przeze mnie serie zdarzeń niepewnych. Cel został osiągnięty na drodze kilkunastoletnich badań własnych, które są

prowadzone na kilkuset obiektach i budowach według autorskiej metodyki oceny i prognozy ich charakterystycznych parametrów (koszt i czas) w warunkach niepewności: od determinizmu, poprzez probabilistykę i przypadkowość, aż do rozmytości. Zarządzanie przedsięwzięciami budowlanymi i podejmowanie decyzji zarządczych następuje w rosnącym stopniu niepewności i wymaga prognozowania przebiegu zadań inwestycyjnych, które zostaną zrealizowane w przyszłości. W prezentowanych badaniach udowodniono, że procesy budowalne powinny być rozważane jako zjawiska ze zdarzeniami losowymi o różnym stopniu niepewności, do których stosować metodykę o zbliżonych parametrach modelowania.

Podejmowanie decyzji w czasie rzeczywistym wydaje się być dobrze rozpoznane jako deterministyczne zdarzenie przyczynowo – skutkowe i jest wspomagane wieloma programami/aplikacjami w codziennej pracy inżynierskiej i menedżerskiej. Znacznie ciekawszym wyzwaniem jest analiza stanów przeszłych o skutkach obserwowanych w teraźniejszości i teraźniejsze modelowanie ciągłych procesów, których efekt będzie widoczny w przyszłości. Przy zastosowaniu logiki dwuwartościowej, gdzie z przesłanki wynika wniosek w sposób arbitralny, decyzja jest zdeterminowania modelem wnioskowania. A w sytuacji gdy taka logika jest niewystarczająca zauważono, że decyzje przestają mieć charakter deterministyczny i stają się wielowariantowe. Również działania podejmowane są wielowariantowo i zakładają śledzenie okoliczności oraz możliwą zmianę w trakcie realizacji decyzji. Nie ulega wątpliwości, że ta rzeczywista sytuacja jest bardziej skomplikowana i w związku z tym wymaga bardziej złożonego procesu zarządzania decyzyjnego. W rzeczywistości inżynier budowlany podejmuje szereg (a nie jedną) interferencyjnych decyzji, które łączą w sobie specyfiki wynikające z przynależności do różnych klas opisanych na skali niepewności decyzyjnej. Dlatego właśnie praktyczne zastosowanie wynikające z prezentowanych w artykule badań sprowadza się do wymodelowania różnych kombinacji sytuacji badawczych i decyzyjnych, które nazwano: „Metodyka prognozowania przebiegu przedsięwzięć budowlanych w warunkach niepewności".

Dane do opracowania autorskiej metodyki badań są wynikiem własnych doświadczeń i pracy zawodowej autora, polegającej na świadczeniu usług Bankowego Inspektora Nadzoru (BIN) w latach 2006–2020 dla banków udzielających kredyty inwestycyjne dla zamówień niepublicznych. W okresie 15 lat gromadzono i przetwarzano dane kosztowe poprzez prowadzenie comiesięcznych, bezpośrednich inspekcji techniczno – finansowych na placach budów realizowanych inwestycji. Pomiar kosztu i budżetu zadań inwestycyjnych udokumentowano w 536 raportach BIN: raportach wstępnych RW, raportach miesięcznych RM, raportach końcowych RK. Badania dotyczyły różnych przedsięwzięć budowlanych w 8 zróżnicowanych typologicznie i ilościowo próbach badawczych: budynki zbiorowego zamieszkania, obiekty biurowe, hotele, parki handlowo-usługowe, centra logistyczne, ośrodki zdrowia, lotniska i zakłady przemysłowe.

Celem modelowania pierwszej części badań było wyznaczenie w sposób mierzalny tych istotnych parametrów zadania inwestycyjnego, które znacząco wpływają na jego późniejszy skumulowany koszt. Celem modelowania drugiej części badań było monitorowanie i projekcja przebiegu zróżnicowanych przedsięwzięć budowlanych w zakresie planowanego, poniesionego i rzeczywiście wypracowanego kosztu oraz wskazanie podstawowych przyczyn odchyleń kosztowych od wartości wypracowanych czyli rzeczywiście wykonanych na budowie.

W badaniach inżynierii procesów budowlanych w warunkach niepewności starano się przeanalizować przedmiot badań podejściem deterministycznym, a tam gdzie to było trudne lub wątpliwe podejściem probabilistycznym i rozmytym. Udowodniono, że pełen determinizm jest ograniczony do mierzalnych wartości poniesionych (wypracowanych i zapłaconych) kosztów, natomiast w zakresie niepewności – tam, gdzie rozkład statystyczny jest trudno wyznaczalny i niejednoznaczny – skutecznym narzędziem badawczym jest kwantyfikacja ryzyka w kierunku wyznaczenia jego istotności oraz rachunek zbiorów rozmytych dla nieprzewidzianych robót budowlanych. Tym samym badania

i analizy całkiem naturalnie dzielą się na dwie części w zakresie niepewności: I – determinizm i ryzyko, II – probabilistyka i rozmytość. Rekapitulując, w prezentowanym w artykule osiągnięciem badawczym jest optymalizacja kosztowa przebiegu procesów budowlanych w warunkach niepewności. Przeprowadzono ocenę rzeczywiście / faktycznie wypracowanych kosztów zadań inwestycyjnych, których trend krzywych skumulowanych przepływów pieniężnych można z dużym dopasowaniem estymować prognozując proces budowlany. Wyznaczono przestrzeń krzywej S planowanych kosztów wielomianem 6-go stopnia, który wskazuje obszar spodziewanych kosztów w przedsięwzięciu budowlanym i szacowane wartości ich odchyleń. Określono przedział rzeczywistych kosztów inwestycji, które – po osiągnięciu 50% zaawansowania rzeczowo-finansowego aż do 80% – generowane są w dużo szybszym tempie niż wynika to z planowania przedinwestycyjnego. Wykazano, że ryzyka inwestycyjne są „zarządzalne”, ponieważ te o największym wpływie występują z niewielkim prawdopodobieństwem, a te o najmniejszym wpływie z prawdopodobieństwem większym, co wskazuje na umiarkowany poziom istotności (1/3) ryzyk procesu budowlanego. Udowodniono, że w kontraktach inżynierskich powykonawczych zdarzenie losowe określone jako nieprzewidziana robota budowlana ma charakter losowy i występuje z określonym prawdopodobieństwem, w kontraktach ryczałtowych natomiast takie zdarzenie losowe ma charakter rozmyty i jego występowanie jest określone liniowo funkcją przynależności do zbioru zdarzeń rozmytych tożsamych z nieprzewidzianymi. Przeprowadzono identyfikację błędów przyczynowych i grupę robót nieprzewidzianych jako dwóch zbiorów rozmytych o niepewnym stopniu występowania, w których tylko wadliwie skonstruowany biznes plan inwestycji i niedoszacowany budżet zadania inwestycyjnego wykazują całkowity i silny wpływ na wszystkie nieprzewidziane działania inwestycyjne w analizowanych przedsięwzięciach budowlanych. Obliczono, że 80% zadań inwestycyjnych kończy się przekroczeniem kosztu, ale do około połowy czasu trwania przedsięwzięcia nie wiadomo czy to przekroczenie wystąpi; celowe wydaje się być szczegółowe badanie niepewności przekroczenia kosztu z fazą rozmytą.

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