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PERSPECTIVES OF PERFORMANCE MEASUREMENT AND MANAGEMENT IN CONSTRUCTION

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PERSPECTIVES OF PERFORMANCE MEASUREMENT AND MANAGEMENT IN CONSTRUCTION

PERSPEKTIVY MĚŘENÍ A ŘÍZENÍ VÝKONNOSTI VE STAVEBNICTVÍ

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in the field of
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Contents

ABOUT AUTHOR **4**

1 INTRODUCTION **7**

2 PERFORMANCE MANAGEMENT AND MEASUREMENT IN THE CONTEXT OF CONSTRUCTION **8**

2.1 Project and organizational level perspective 10

2.2 Stakeholder’s perspective 12

3 SHIFTING FROM TRADITIONAL PERFORMANCE MANAGEMENT AND MOVING BEYOND ITS CONVENTIONAL CAPABILITIES **13**

3.1 Procurement and cost estimation perspective 14

3.2 Sustainability perspective 18

3.3 Prospects for further development of performance management systems 22

4 CONCLUSION **24**

5 CONCEPT OF FUTURE ACTIVITIES IN RESEARCH AND TEACHING **25**

REFERENCES **27**

CZECH ABSTRAKT (Shrnutí) **32**

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1 INTRODUCTION

Construction projects are characterized by their high resource requirements, be they material, human or financial. Their outputs are built construction objects creating living space for people, but also other living organisms, in the long term. With regard to the real impacts of construction projects on various stakeholders, their surroundings, but also from the economic point of view on investors' budgets, due attention must be paid to whether the set project goals are being achieved. The basic characteristics of construction projects include, among others, a high degree of complexity, a high number of project participants, a wide range of risks, as well as the significant and permanent sequence of changes occurring in parallel during various stages of the project's life cycle. Taking these characteristics into account, it is clear that successfully managing such a complex system consisting of many sub-processes and activities represents a demanding activity with a lot of responsibility.

The assumption for the successful management and completion of the project and the subsequent operation of an existing structure is the process of control. In order to control, one must also measure, i.e. continuously identify, monitor and evaluate the values of key parameters that are essential in the context of achieving the set goals. Therefore, performance measurement represents an integral part of management [1] and should be followed by a dynamic and interdisciplinary approach within the construction sector.

The main task of managers is to ensure the success of projects and, indeed, many projects have been successful in terms of their fundamental aspects. The *Heathrow Terminal 5* project is a well-known example around the world because it was completed on time, within the budget and in the required quality. However, projects that did not meet the defined parameters can be encountered much more often. Staying in the realm of aviation infrastructure projects, the *Berlin Brandenburg Airport* project represents an extreme case of failure, as it was finished with a ten-year delay and multiple budget overruns.

For effective performance management, it is crucial to determine the conditions for success. The theory of project management historically recognised the "iron triangle" (also referred to as the triple constraint) which defined a successful project as being completed on time, at planned costs and in the required quality. The Iron Triangle concept has gained great popularity due to the good and easy measurability of the criteria; however, it has been criticized for a long time because it fails to deal with the success of the project from a broader perspective [2]. Time, cost and quality will always belong to the basic criteria, but should be supplemented by other areas of control resulting from the specific characteristics of the construction industry (e.g., risks, complexity and long life cycle). In other words, the required levels of performance (in terms of time, cost and quality) can only be achieved if other areas are monitored and evaluated too.

Construction is recognized as a project-oriented industry. Therefore, performance improvement efforts on the organizational level (regardless of whether this concerns the supplier, investor or another type of organization) significantly depends on the project-level performance. The author's professional activities, which focus on areas such as business economics and cost estimation issues in construction, necessarily reflect the interactions between the supply side and the demand (customer) side. Understanding different views of stakeholders on priorities regarding the expected performance, therefore, contributes to the higher overall satisfaction with construction outputs. The following chapters present selected key traditional perspectives of performance management in the context of construction, which are followed by advanced and proliferating perspectives grounded in recent development trends and requirements. The individual perspectives are supplemented with the presentation of the author's scientific work outputs in the field of *Civil Engineering Management*.

2 PERFORMANCE MANAGEMENT AND MEASUREMENT IN THE CONTEXT OF CONSTRUCTION

Achieving the required performance depends on the right choice of individual metrics. In construction, each project is unique, even though a similar set of activities and processes are performed in every project. Therefore, it becomes problematic to determine unambiguously what should actually be measured. This issue is addressed in the following sections.

Performance management and measurement represent a tool facilitating the control of processes. The literature [3] suggests considering three dimensions of control, namely control types, degree and style. Procedural controls contributing to efficiency improvement (e.g., tracking project milestones), social controls focusing on shared understanding (e.g., exchange of information) and hybrid controls (e.g., site visits) represent particular control types. Control degree expresses the number/intensity of controls, which can be tight or relaxed; and regarding control style, one may consider unilateral control (when client typically controls the other party) or bilateral control (client and second party use control mechanisms jointly).

From the perspective of the construction industry, hybrid and tight controls should be recommended as a suitable way of controlling the project, as it is necessary not only to formally check compliance with milestones but also to monitor the progress and the quality of the works carried out on the construction site on a regular and frequent basis. Regarding the control style, multilateral control should be considered given the large number of stakeholders involved (see more in Section 2.2). As suggested by Koppenjan [4], control should be balanced with flexibility, two competing approaches, as projects are the subject of frequent changes and adjustments.

For completed and operational facilities, the dimensions of control might be different when compared to the execution of construction works; nevertheless, it might vary also with respect to a particular building. On the one hand, the controls need not be too frequent (e.g., observation of defects in outside thermal insulations systems), on the other hand, real-time data monitoring is needed for critical infrastructure in particular.

When defining appropriate metrics, one should take into consideration the following suggestions: a metric must (a) provide value to stakeholders, (b) establish an objective target, (c) focus on continuous improvement, and (d) provide timely and accurate feedback [5,6]. In this view, an appropriate scale of measurement has to be applied. The literature recognises nominal and ordinal scales for qualitative data and interval and ratio scales for quantitative data. Each type of scale has its place in specific situations, e.g. nominal scale might be applied for qualification assessment, while there are numerous financial ratios (i.e., ratio scale) used to perform quantitative analysis (to assess e.g. company's liquidity, profitability, rates of return, growth, or valuation).

As an example, various approaches to cost performance can be presented. One should consider a simple type of an indicator such as Cost Variance (*CV*), calculated for projects already completed (CV_F) as a difference between Budgeted Cost of Work Performed (*BCWP*) and Actual Cost of Work Performed (*ACWP*):

$$CV_F = BCWP - ACWP \, , \tag{1}$$

or as a difference between Earned Value (*EV*) at a certain moment and actual costs (*AC*) at the same moment as suggested for ongoing projects (CV_O) by Earned Value Management [7]:

$$CV_O = EV - AC \, . \tag{2}$$

Furthermore, various types of ratio indicators are available, such as Cost Performance Index (*CPI*) representing a ratio between *EV* and *AC* and Design Cost Predictability (*DCP*) [8] comparing Performed Design Costs (*PeDC*) and Planned Design Costs (*PlDC*):

$$CPI = \frac{EV}{AC} \, , \tag{3}$$

$$DCP = \frac{PeDC - PlDC}{PlDC} \, . \tag{4}$$

The literature also suggests advanced indicators, for example monitoring a certain indicator from the risk management point of view. For cost estimation, Cost Risk Performance Index (*CRPI*) is proposed [9] comparing residual cost risk variance (*RCRV*) and forecast cost risk variance (*FCRV*) at a specific point during the project period, calculated based on the following equation:

$$CRPI = \frac{FCRV - RCRV}{FCRV} \, . \tag{5}$$

Accordingly, *CRPI* = 1 indicates that *RCRV* = 0, thus situation when all cost risks have been eliminated, CRPI = 0 indicates unchanged status, *CRPI* between (0 – 1) positive progress (residual cost risks are smaller than forecasted) and *CRPI* < 0 negative progress (*RCRI* > *FCRV*). As long as construction projects are subject to frequent changes, Revised Estimated Value (*REV*) also deserves attention [10], and accordingly, the equation (2) is modified to Revised Cost Performance Index (CPI_R):

$$CPI_R = \frac{REV}{AC} \, , \tag{6}$$

which in terms of *REV* covers changes resulting from amendments to work contracts or other changes that may occur during implementation. Earned Value Management also allows to forecast final project costs [11]; several calculations methods of Estimate at Completion (*EAC*) are suggested with respect to the accuracy of original estimation. For instance, if the original estimate is met, then the following equation might be used:

$$EAC = \frac{BAC}{CPI} \, , \tag{7}$$

where *BAC* stands for Budget at Completion established earlier in the contract. Taking high variability of available indicators into consideration, one should pay attention to how to measure a specific feature/activity.

2.1 Project and organizational level perspective

Performance management systems should be built on management control theory addressing "pragmatic concern for results, obtained through people" and connected to formal control systems (e.g. budgeting) [12]. According to Hofstede's theory, management control in construction is not effortless and simple because some of the stated assumptions (objectives are definite, outputs are measurable, effects of interventions are known, and the process/activity is repetitive) appear to be quite challenging. Furthermore, as Radujković et al. [13] have highlighted, despite significant theoretical achievements no consensus has been reached on what makes a project successful, what constitutes a project success and how to plan and deliver a successful project. This background certainly impedes the easy adoption of performance management on the construction project level.

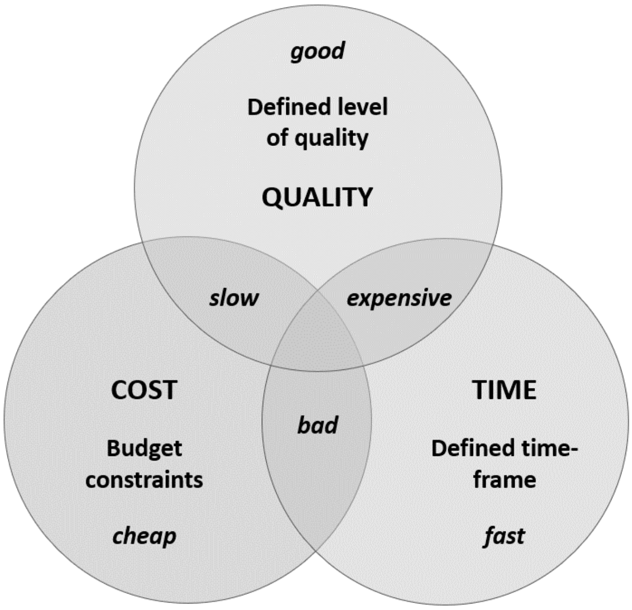

Figure 1. *The concept of Triple Constraint, based on* [2,14]

Table 1. *The most common performance areas on the construction project level (based on* [8,15,16]*)*

Performance area	Examples of performance indicators
Cost	Cost efficiency, construction cost prediction, budget reduction rate
Time	Schedule efficiency, time savings, overtime work rate
Quality	Defect frequency, rework rate
Productivity	Labour productivity, machinery productivity
Safety	Registered unwanted occurrences, lost-time injuries,
Stakeholders (satisfaction)	Stakeholder empowerment, stakeholders right protection, client's satisfaction
Environment/sustainability	Demolition/reuse rate, impact on soil/land resources

The following most common seven performance areas have been identified in the available literature (see Table 1). The list of areas starts with three aspects of the Iron Triangle (see Figure 1), followed by the areas of productivity, safety, stakeholder and the environment. Obviously, other criteria are also considered on the project level such as profitability (a financial metric) and security (e.g., number of thefts). The data show an expanding range of measurement areas, such as the focus on safety and monitoring of satisfaction with regard to the customer or team members, that has later developed into stakeholder management. Finally, the ecological and sustainability considerations come to the forefront in response to the increasing concerns about environmental protection.

A recent study [17] on the suppliers' performance management in construction on the project level in the Czech Republic revealed the highest usage of performance measurement among medium-sized and large supplier companies (all the respondents participating in the survey reported that they measure their contracts to a certain extent), while only 50% of micro and small companies applied some form of performance management. Similarly, the size of the company also affects the measurement time range. Most micro and small companies measure their projects only after completion; on the contrary, medium-sized and large companies usually monitor the performance already during the execution of construction works. This finding confirms the assumption that sufficient staff is needed to measure performance and, therefore, might represent a significant limitation for smaller companies.

Regarding individual indicators (see Figure 2), construction cost, construction time and client satisfaction are ranked among the top three most frequently used. The fact that quality ranked the fifth (a relatively low position) can be explained by a higher emphasis on client satisfaction that also includes, to some extent, the evaluation of delivered quality.

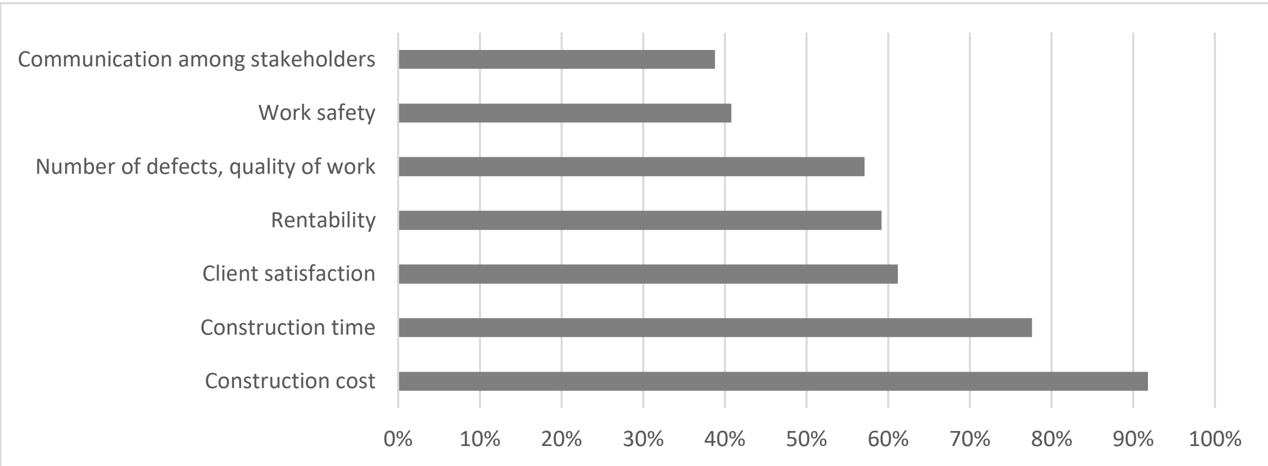

Figure 2. *Relative frequency of use of performance indicators by construction companies* [17]

Because construction companies implement contracts in the form of projects, the performance achieved at the project level affects performance on the organizational level as well. The available literature suggests several performance management models for the construction industry, namely the BSC (Balanced Scorecard) based models, EFQM (European Foundation for Quality Management) based models and KPI (Key Performance Indicators) based models. Each model has certain advantages and disadvantages; while BSC favours a clear focus on strategy, it has been criticized for not having comprehensive feedback from the financial to other perspectives [18,19].

Apart from the financial perspective, BSC also covers internal processes, client/investor and innovation and learning. EFQM looks at the performance through nine weighted criteria and recognizes lagging and leading indicators (i.e., enablers and results, respectively). Although EFQM has been widely adopted in construction, it has also been criticized mostly for its insufficient strategic focus [20].

Apart from performance areas suggested by BSC and EFQM, the KPI-based performance models might apply another structure of criteria. For instance, a set of 20 performance attributes has been proposed by [21], five base metrics (schedule performance, cost performance, safety performance, customer satisfaction, and profit) are reported in [22]. In this case, customer satisfaction measurement is suggested in terms of the percentage of repeat business customers. Such an approach might be applicable for private construction projects or subcontractors; however, in public projects, the duration of buyer-supplier relation is typically limited to a single contract [23]. Therefore, due to the specific features of the construction industry, general models should be adjusted accordingly by adding or modifying specific performance indicators.

2.2 Stakeholder's perspective

Available theory, as well as construction management practice, recognizes the importance of stakeholder management within civil engineering. According to Freeman and McVea, the idea of stakeholder management „*suggests that managers must formulate and implement processes which satisfy all and only those groups who have a stake in the business*" [24]. They pinpointed the necessity to "*satisfy multiple stakeholders simultaneously*", which is especially challenging in a construction project environment where the number of stakeholders can be high, representing numerous interfaces and even conflicting expectations that have to be managed. The example of a comprehensive stakeholder identification with regard to the Big City Road Circuit Brno covering a wide range of internal (demand and supply side) and external (public and private) entities can be mentioned in this context [25].

Based on Mitchell's theory [26], the following key constructs for stakeholder identification and salience are noted: (1) power, to influence the project; (2) legitimacy, to have a relationship with the project; and (3) urgency, claims call for immediate action. Based on these assumptions, the client (investor), supplier and supervising engineers (consultants) are usually considered key stakeholders. However, having in mind the specificity of individual projects, in the case of PPP (Public-Private Partnership) projects that are typical for road constructions the literature suggests to also consider users that use the facility and are, for example, interested in completion of the project on time as a key stakeholder [27].

The fact that individual stakeholders view construction projects differently in certain aspects has been examined and ensues from having various aims [27,28]. If a collaborative environment is created between the stakeholders, the project itself could benefit from enhanced cost performance [29]. For instance, better coordination and communication among stakeholders contribute to the satisfaction of the participants with the quality of structures [30].

The author has recently participated in a research task as part of an international scientific project addressing the ways in which the stakeholders' point of view differs in terms of performance management on the project level. The results of an in-depth analysis of a multiple case study have revealed a wide spectrum of causes that reduce performance. These involve, among others, mostly the insufficient quality of project documentation resulting in unforeseen/not designed works or unneeded works, the interruption of works due to the discovery of historical remains and the subsequent archaeological research, insufficient communication among stakeholders, poor cost estimates and problems among the members of a consortium of companies. Concerning the performance perception, cross-case conclusions have pinpointed considerable differences between investors on the one hand and suppliers and supervising engineers on the other hand (e.g., while investors accentuate the delivery time, both suppliers and supervising engineers focus more on safety issues).

Data from the Czech construction practice [17,31] shows that larger companies usually use more sophisticated performance management systems and that the level of measurement also depends on the project scope. For larger contracts, more time is devoted to the actual measurement of ongoing projects by specialized employees. Regarding two metrics of the Iron Triangle, the cost/schedule variance are more often used than the cost/schedule performance index (i.e., ratio indicator); furthermore, performance evaluation is often mostly based on data processed in Microsoft Excel, followed by Microsoft Project.

Companies recognize the quality of inputs for the tender and insufficient communication between stakeholders as crucial factors influencing project outputs. Accordingly, the occurrence of information asymmetry [32] within the construction project should be reduced to support smooth communication flow. On the other hand, public investors usually do not conduct adequate and comprehensive measurements. For instance, they estimate the quality of the delivery (e.g., in terms of the number of claims), but a more detailed approach is only applied when the project fails in relation to its basic targets.

A comparison of results obtained within own research activities and data in similar research studies published so far confirms that no consensus has been reached on the range of metrics that should be monitored. The successful management of stakeholders also assumes the incorporation into the performance management system of an incentive/disincentive mechanism allowing to reward excellent performance and penalize poor results [33].

3 SHIFTING FROM TRADITIONAL PERFORMANCE MANAGEMENT AND MOVING BEYOND ITS CONVENTIONAL CAPABILITIES

Traditional performance management based on an extended interpretation of the Iron Triangle appears to be insufficient in the light of new developments, requirements, expectations and research achievements. Firstly, there is a call for a tighter inclusion of procurement and cost estimation issues within the evaluation of performance. Secondly, long-term monitoring of cost performance in the field of construction management represented by the Life-Cycle Costing approach can be seen as one of the major challenges for both researchers and practitioners. Finally, a broader approach to sustainability issues is needed, especially from the environmental perspective. The following sections aim to address these issues and present some of the author's results that have contributed to the development of the above-mentioned areas.

3.1 Procurement and cost estimation perspective

Even though the Project Management Institute [34] classifies "procurement" among the 14 core areas of performance, in practice, it is often not involved in the actual evaluation. The primary function of procurement is to get the right product/service/work at the right price and from a capable contractor. Main endeavours of investors are being made towards achieving high financial performance, which depends on the effective price negotiation, selection of effective project delivery method, contractual management and ensuring the required supply quality. For instance, the Best Value Approach (BVA), which emphasises the price/value ratio, appears to be highly suitable from a performance management perspective as it considers the performance of tenderers [35].

Accordingly, careful attention should be paid to the qualification process and evaluation of bids as key steps in selecting an eligible supplier. In this regard, one should take into consideration the legislative requirements (the Public Procurement Act) and, at the same time, the nature of particular construction investment. The author of this thesis has collaborated on an international comparative study of the Czech Republic and Poland. On the sample of 345 construction projects (roads, schools and water/sewage), contracting authorities' practices in the field of qualification were examined [36]. Results confirmed different use of certain qualification criteria from the perspective of the type of contract, as well as from a cross-national point of view. Partial outputs of the research relating to the professional and technical qualifications are shown in Table 2.

Table 2. *Evidence of relative frequency of occurrence in % on professional and technical qualification criteria* [36]

Qualification criteria	Roads		Schools		Water/Sewage	
Professional	CZ	PL	CZ	PL	CZ	PL
Evidence of possession of a licence	94.1		93.2		98.3	
Evidence issued by a professional self-governing chamber	1.5		6.8		10.2	
Authorisations to perform specific activities or actions	98.5	0.0	76.3	0.0	78.0	17.0
Evidence proving the economic operator´s capability to safeguard the confidentiality	0.0		3.4		0.0	
Technical	CZ	PL	CZ	PL	CZ	PL
Declaration that persons participating in contract have required qualification/licence	32.4	66.0	28.3	68.0	47.5	93.0
List of personnel	11.8	60.0	28.3	90.0	22.0	90.0
List of tools, equipment and technical devices	52.9	20.0	0.0	0.0	8.5	2.0
List of works with documents confirming if previous works were performed properly	100.0	90.0	100.0	100.0	100.0	95.0
Average no. of personnel annually	7.4	0.0	6.8	0.0	0.0	0.0
Minimal volume of works on contract	2.9	24.0	86.4	72.0	91.5	52.0

The findings are in line with the conclusions of Patrucco et al. [23] on the positive effect of a proper qualification stage on the performance of (e.g., infrastructure) projects. On the other hand, suppliers should be aware of the qualification requirements used by investors to be able to successfully bid for contracts and thus help to fulfil the production plan and improve the capacity utilization performance metric.

The follow-up analysis further examined the approach of public investors to the process of evaluation of the bids submitted [37]. In contrast to qualification, significant differences between the use of evaluation criteria have not been found between the Czech Republic and Poland as evaluation is primarily based on the lowest bid price. Just 8.7% of the analysed projects were evaluated by using multiple criteria, e.g. duration of works, warranty period and operating costs. The data suggest that the LCC approach is still not very widespread among public investors in both the Czech Republic and Poland.

A detailed investigation of this topic has also resulted in the development of the "Methodological recommendations for the unification of qualification and valuation criteria for public works contracts" [38] that were adopted by the South Moravian Region for practical use within the Region's authorities as well as its subordinate organizations.

The bid price is an important element influencing the financial aspect of construction projects. In this area, the author has conducted an analysis of how the competition in tender measured by the number of bidders affected the ratio between the award price and the estimated price (AE_r) [39]. Results based on a dataset of 256 tenders suggest an increasing trend of achieving more favourable (i.e., lower) bid prices with the increasing level of competition within the tender (see Figure 3). The results obtained are consistent with other studies published so far centring attention to encouraging sufficient competition in the tender (e.g. [40]) as a focal point of the tender process.

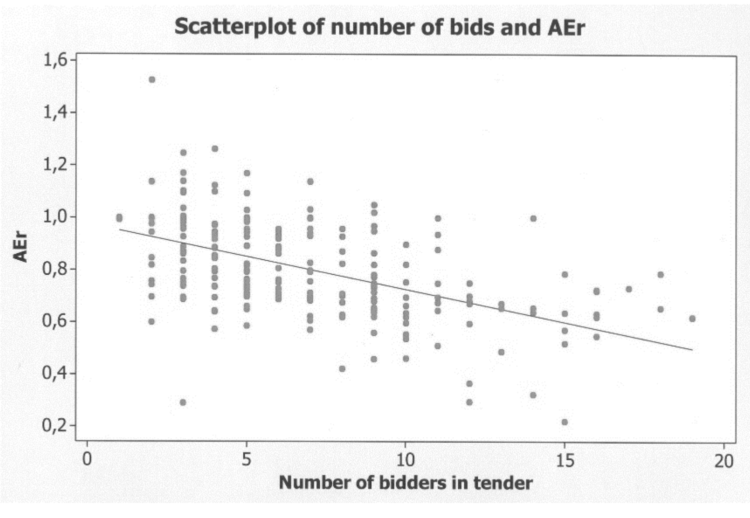

Figure 3. *Analysis of the dependence of relationship between AE_r at the number of bidders* [39]

A further author's research activity has been directed towards an innovative procurement route supporting the digitalization of the purchasing process consisting of electronic reverse auctions (e-RA). Despite the controversy related to e-RA use in the construction sector, research results have shown the benefits of their application for buyers (e.g., cost savings and enhanced transparency) and partially also for suppliers (equal opportunity to get the contract). However, an informed decision on using e-RA should be made with respect to the need to critically review the suitability of auctions with regard to the nature of the product required and the ability of the buyer to describe it in sufficient detail [41,42]. An in-depth exploration of savings potential conducted on the Slovak e-RA dataset (161 records) proved that a significant proportion of e-RA-supported tenders (52.8%) dealt with a low number of bidders (that is less than 4). However, if sufficient competition within the tender is ensured, the buyer may enjoy significant savings achieved through the auction. As an example, Figure 4 shows contour plots for the estimation of the achieved relative savings percentage for the "buildings" subset (where *nNOB* stands for the number of bidders and *nCHA* for the number of changes of bids during the comparison round) [43]. Accordingly, efforts towards strengthening the competition and using competition-oriented tolls have the ambition to bring about further performance improvement.

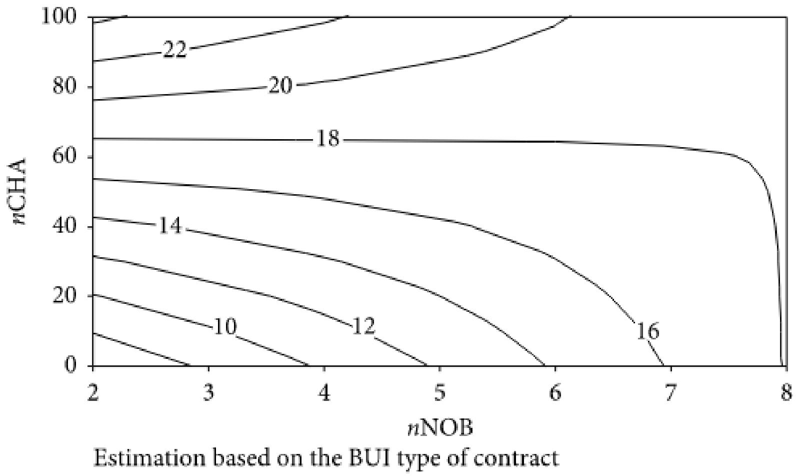

Figure 4. *Contour plot for the estimation of the achieved relative savings percentage ("buildings" subset)* [43]

Regarding the bidding process, the issue of bid price estimation deserves some attention. Firstly, from the investor's point of view, the estimated value of the contract may be not determined adequately. For instance, cost estimation based on what is called "technical-economic indicators" might provide considerably misleading outputs in the case of less common facilities because these indicators are often built on small datasets of historical prices and indexed to the actual price levels. A case study analysis of sports facilities revealed a large discrepancy between publicly available indicators and real data coming from executed projects. Table 3 shows the comparison of the values of the technical-economic indicator per 1 m^3 of enclosed area (TEI_{EA}) with ÚRS and RTS indicators [EUR/m^3]. The results clearly indicate that using ÚRS and RTS indicators leads to the overestimation of investment costs [44].

Table 3. Comparison of TEI_{EA} values with ÚRS and RTS indicators [EUR/m^3], [44]

Indicator	TEI_{EA}	ÚRS	RTS
Sample size	7	3	unknown
Value	118.23	213.95	204.10
Relative difference	100%	181%	173%

The accuracy of preliminary/estimated values becomes important inasmuch as a significant part of contractors may be influenced by them when determining their bid price. The research on bidding strategy in construction public procurement [45] has documented that less successful companies in tenders pay more attention to the estimated value than moderately and highly successful companies. The estimated value should be considered rather as an indicative value, not a binding basis for the bid price assessment. In the Czech construction sector, most of the suppliers apply cost-oriented pricing methods; however, the bidding strategy may be differentiated in appealing tenders as a response to the low-cost orientation of the Czech public construction procurement. The accuracy of cost estimation may also be negatively influenced by faulty overheads management. A detailed analysis of 16 bridge construction projects has revealed significant shortcomings in the calculation process [46]. The findings helped identify the three most important production overhead cost (POC) items for individual contracts (see Figure 5) and formulate several recommendations on how to improve the calculation process. The follow-up research has confirmed that overheads calculation affect the company's competitiveness on the market and, consequently, its ability to win contracts [47].

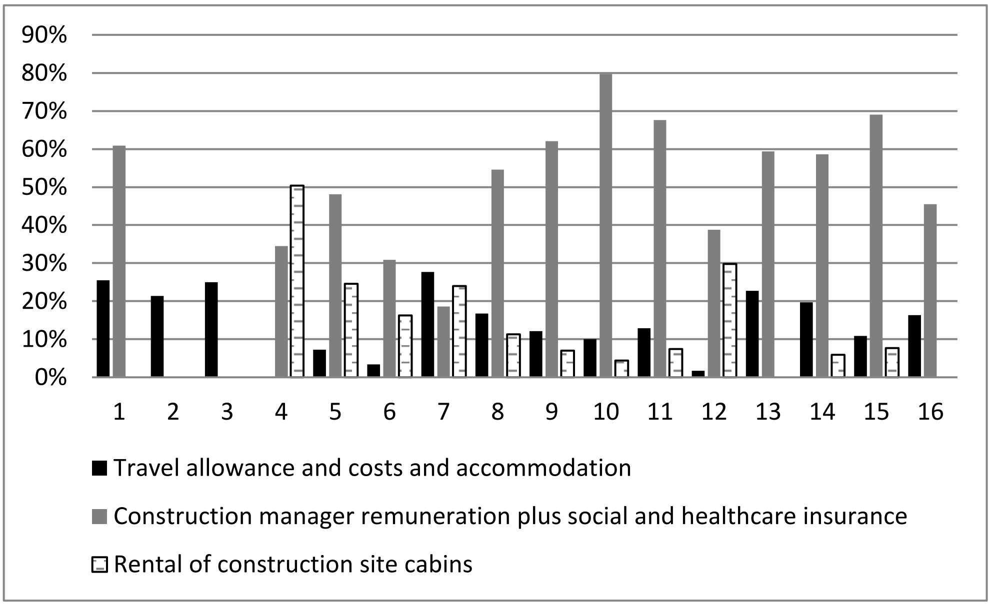

Figure 5. *Comparison of the share of the three most important POC items for the individual contracts on total POC* [46]

The results from the procurement stage should later be confronted with the actual costs resulting from the execution of the project. A study of 16 South Moravian road construction projects (see Figure 6) has revealed a high interest of tenderers in competing. Accordingly, market competition has significantly reduced award price compared to the estimated value; however, the difference between the award (or contract) price and the final (or actual) price points to the later changes in the project due to various implementation reasons, such as conflicts with existing utility networks or insufficient design and exploratory works (e.g., the occurrence of subsoil with insufficient bearing capacity) [48]. Thus, the outputs of this study emphasize again the unsatisfactory quality of available tender documentation as a factor with significant potential to influence the performance.

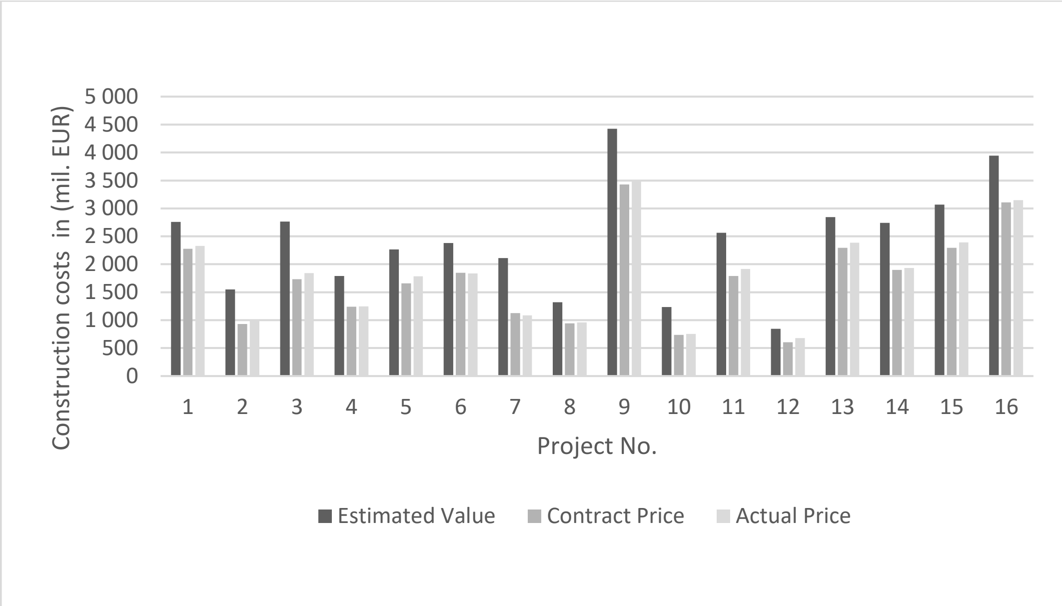

Figure 6. *Comparison of value/prices in individual project phases* [48]

3.2 Sustainability perspective

The drive towards sustainability has many dimensions. In construction and facility management, these involve a decrease in energy demands, efficient maintenance solutions, the use of environment-friendly materials, issues related to the recycling/reuse of materials at the end of the structure's lifetime and thus also the issue of a circular economy. Within the field of "Civil Engineering Management", we are especially interested in the related economic aspects. Therefore, the cost perspective should cover not just project execution costs and other costs relating to the early stages of the project (e.g., costs for project documentation), but also costs incurred during the operational phase and the costs of disposal. Thus, scholars refer to Life-Cycle Costs (LCC) to look for cost-optimal solutions throughout the entire service life of a building or facility [49,50]. The most common LCC calculation formula is

$$LCC = \sum_{n=0}^{t} \frac{c_n}{(1+r)^n} \ , \qquad (8)$$

where c_n denotes all annual costs in year n,

r is the discount rate,

n is the analysed year (n = 0, 1, 2, … t),

t is the length of the life-cycle in years.

People managing and preparing projects face the problem of the lack of accurate data in its early stages. The closer they are to the beginning of the project, the more difficult it is to estimate or predict not just execution costs, but especially the consequent operational costs. The current body of knowledge suggests several advanced methods for quick cost prediction, for instance in tunnel or road structures [51,52], but their actual application in practice is minimal.

Furthermore, the unavailability of precise data on costs of expected repairs and maintenance, as well as determining the proper expected service life of structures complicates LCC predictions in the more distant future. In this regard, Construction 4.0 should facilitate working with the necessary data and many practitioners expect significant benefits from the deployment of BIM (Building Information Management). The practical use of BIM represents a significant transformation of the entire industry and is associated with revolutionary digitalization and automation advances [53]. As stated by Gledson & Greenwood [54], BIM adoption rates vary across the world. For the UK, increased use of 4D BIM for planning projects has been reported in 2017 with a time lag of 2.38-3.00 years between awareness of it and the first use. Recent pilot BIM projects implemented in the Czech Republic have aimed to identify and verify options of, for example, design optimization with respect to investor requirements, BIM use during the operation of the building and during renovations.

In this area, the author participated in the creation of an LCC estimation model focusing on construction materials [55]. The model builds on the formula (7) given above, populating the repair, maintenance and replacement (R/M/R) database with relevant data (information on R/M/R costs is transferred from the price framework of the building cost estimation system). Because the model connects three different systems: (1) the LCC calculation system; (2) the facility management system; and (3) the building cost estimation system, it was necessary to establish a suitable structural division of a building that would be compatible with all the component systems, i.e., dividing it into functional parts (see Figure 7). The model is assembled for a selected functional part of the building (Façade Composition). The model provides information on acquisition costs, replacement costs, maintenance costs and repair costs and thus supports investors with relevant LCC data that facilitate making informed decisions regarding the selection of optimum material solutions for their buildings.

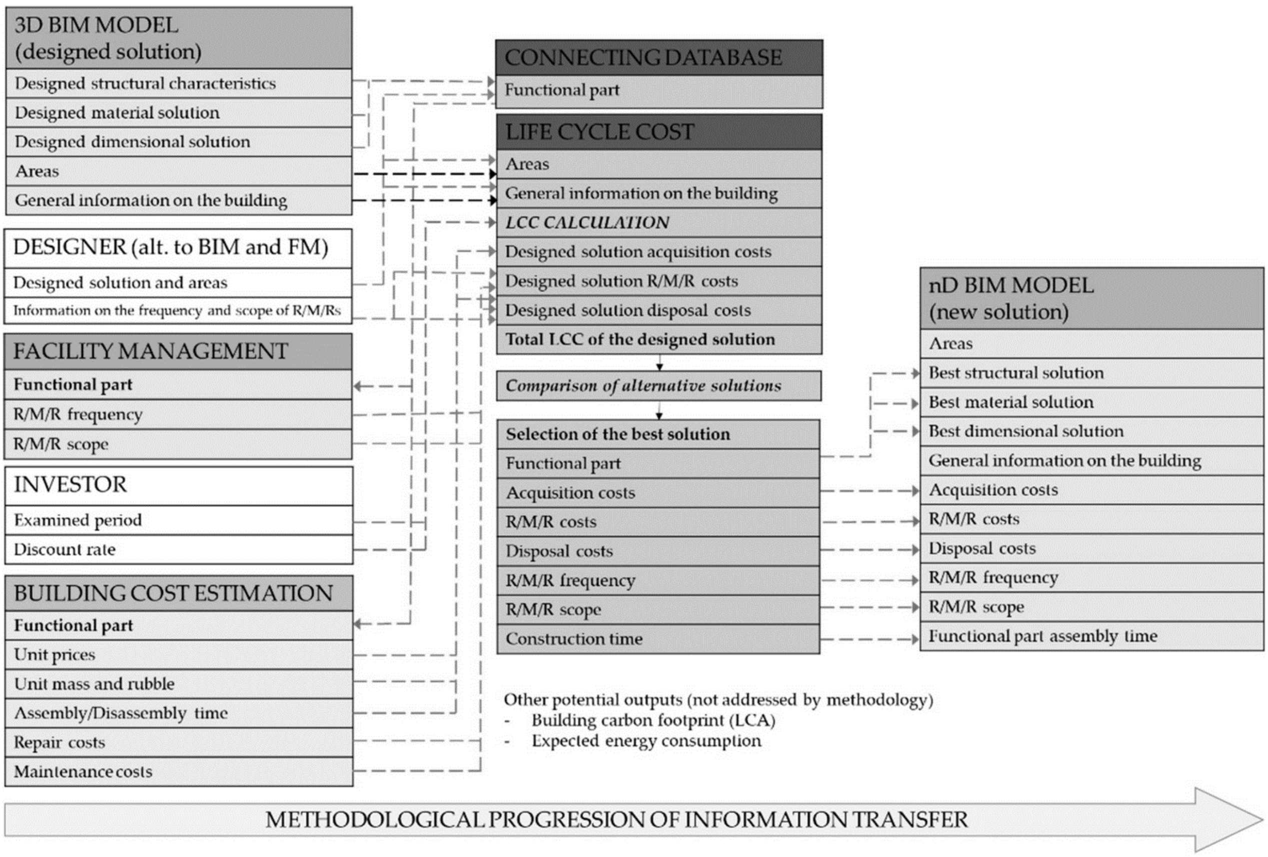

Figure 7. *The process of exchanging information among the individual systems* [55]

The introduced model received a great deal of attention in the research community, which can be demonstrated by the high number of citations (more than 20 citations on Web of Science, as well as in the Scopus database within two years of publication); furthermore, the paper got the "Buildings" journal's Best Paper Award in 2019 (second award) based on the evaluation of the originality and significance of the paper, its citations, and downloads.

Currently, the proposed model is being developed further to extend its applicability to the early stages of construction projects (especially the design stage) in order to demonstrate a wide range of possible design and material solutions with diverse LCC. Such approach is vital mostly for investors, but becomes no less important for contractors, for example under the Build-Operate-Transfer arrangements [56] where the contractor is also appointed to operate and maintain the project on behalf of the client for an agreed period of time. When creating the concept for selecting the best contractor based on Multi-Criteria Decision Analysis (MCDA), different perceptions of the long-term cost perspective has been revealed among clients and suppliers [57]. While the weight of life-cycle costs for clients was 24.9% (that is more than the weight of the criterion of quality), for contractors the weight was just 4.9%.

For existing buildings/structures/facilities, the management and the related optimization of their operation and maintenance should be considered. The set of modern optimisation modelling tools has been reviewed in [58] and supplemented with the call for involving optimization methods and information systems in decision-making. For instance, the maximum increase in winter road maintenance service in Kraljevica to ensure steady traffic conditions has been examined. The problem has been addressed in terms of the capacitated vehicle routing problem and a simulation was based on the worst weather scenario. The results of the advanced analysis revealed room for improving maintenance services in small municipalities [59].

The sustainability aspect in construction may also be considered in terms of the related socio-economic impacts. The current body of knowledge provides interesting achievements in this regard, for example in relation to the determination of benefits associated with increasing the safety and reliability of a railway line [60] or an environmentally-friendly design of marine construction supporting enhanced biodiversity [61]. Even though numerous studies have highlighted environmental considerations, this agenda deserves more attention from the research community, especially in the context of Construction 5.0.

Recent trends push this dimension to be incorporated in performance management systems through adding social aspects and commitment to sustainable development goals [62]. An overview of various systems used for performance measurement in construction contracts with emphasis on environmental aspects is available in [63]. The latest findings [64] confirmed that major infrastructure operators (road, rail, utility tunnels, water and sewage) do consider advanced approaches; however, they are not used in practice (or are used in a limited way), whether in terms of BIM, LCC or sustainability in general.

The ongoing Covid-19 pandemic pointed out the importance of ensuring sustainable supply chains in the construction industry. Recent studies analysing the impact of the pandemic on construction projects reported its direct impact on disruptions of the supply chains, workforce immobility and shutdowns of transportation systems resulting in cancellation of planned projects and delays/suspension of existing projects, loss of workforce and financial issues [65,66]. These effects naturally resulted in reduced productivity and, therefore, not meeting performance goals [67].

An exploratory study performed in the context of the Czech construction sector has reported similar issues, such as slowed supply chains (especially for deliveries outside the EU, e.g., a delay in delivery of special cooling equipment from Turkey, delivery of cross-ties for a railway reconstruction to Slovakia from Serbia via Hungary, and the lack of plastic or steel products), project delays/interruptions, lack of personal protective equipment and lengthy dealings with the authorities. Furthermore, some companies have also highlighted the costs incurred in relation to the purchase of additional electronic equipment/devices [68] enabling digitalization and online communication among project participants to reduce the number of face-to-face meetings.

Regarding the investigations of supplier selection [69], it has been confirmed that selection criteria vary among main contractors and subcontractors. While for the main contractors, the major criterion consists of communication and long-term cooperation (they prefer to cooperate with verified suppliers with whom they have developed a long-term relationship), subcontractors focus more on the quality of materials used (they usually bear the ultimate responsibility for the quality of materials as any complaints (claims of defects) in this respect on the part of the client will be shifted from the main contractor to the subcontractors).

Table 4. Significance of performance measurement criteria (RII – relative importance index) used [69]

Main contractors			Subcontractors		
Criterion	RII	Rank	Criterion	RII	Rank
Quality of communication	0.736	6	Quality of communication	0.781	6
Meeting delivery deadlines	0.933	2	Meeting delivery deadlines	0.945	1
Number of claims of defects	0.776	5	Number of claims of defects	0.782	5
Speed in remedying claims of defects	0.840	3	Speed in remedying claims of defects	0.790	4
Ability to flexibly respond to changes in the project	0.829	4	Ability to flexibly respond to changes in the project	0.863	3
Meeting the planned price	0.948	1	Meeting the planned price	0.864	2

Table 4 shows the significance of performance criteria in terms of the relative importance index (RII) according to the role of the company in the supply chain, that is its position as the main contractor or a subcontractor. The data indicate that both main contractors and subcontractors focus mostly on cost and time; furthermore, their swiftness in remedying defects and the ability to flexibly respond to changes in the project are perceived as more important than quality. About half of the companies evaluate their suppliers once a year, the others more often (quarterly or even after each project).

Accordingly, understanding the preferences and expectations of individual stakeholders in the supply chain is essential to promote mutual understanding and building of trust in their relationship. Performance indicators should support achieving project success. In this view, the importance of performance indicators should be continuously re-examined as the project is progressing to its other stages [70]. Consequently, it can be expected that good performance results on the project level will be reflected in better performance on the organizational level.

3.3 Prospects for further development of performance management systems

The findings presented in the previous sections of this thesis emphasized the need to adjust the currently used performance management systems in construction to address new requirements and challenges. Accordingly, this calls for a re-examination of the suitability of the KPI used and exploration of various other influences that affect the economics of construction projects.

There are several points to be highlighted. Firstly, we should be aware that setting performance targets must be based on realistic expectations and should lead to a successful conclusion of the project. From the economic point of view, this requires the adoption of refined/advanced tools (such as refined values of technical-economic indicators [44], neural networks, support-vector machines or genetic algorithms [51,52,71]) in order to improve cost estimations. The preparation of tender documentation, as well as the procurement stage, should rely more on the long-term perspective represented by the LCC approach [50,55] and the selection of a capable supplier based on sound qualifications and reasonable and efficient valuation criteria [36,37]. The execution phase has to be monitored by a comprehensive set of indicators covering the Iron Triangle, as well as other performance areas [8,15] and to consider stakeholder management, as well as management of the supply chain [17,26,64,68,69].

An in-depth post-project review is needed during the post-construction phase, which has to be supplemented with a list of informative insights for the future, as well as analysis of challenges and solutions adopted during the project execution [46] [SUS]. Accordingly, defining requirements for the post-construction audit seems to be a crucial issue. The positive effect of the LCC approach should later be monitored within facility management during the operational phase [72], as well as in the context of sustainability that becomes important during the disposal phase.

In order to monitor performance areas adequately, appropriate KPIs [15,17,64,69] must be defined with respect to the informative value they are providing for particular activities and in individual stages of the particular type of project. KPIs should be used in a progressive way allowing for the prediction of future performance and support risk control. Therefore, both the setting of the project's objectives as well as the project's reporting should be based on KPIs. It is expected that enhanced digitalization will further contribute to enhanced productivity in the construction industry.

Figure 8 clearly shows the key issues (processes in particular stages) relating to the performance management and measurement in construction from an economic point of view. Additionally, the cloud-shaped bubbles outline the recommended direction of future research for performance management improvement, while line bubble labels show examples of cost performance indicators variability. Further investigations should also be directed towards creating a link to the organisational strategy and decomposition of strategic goals into particular KPIs [18,73].

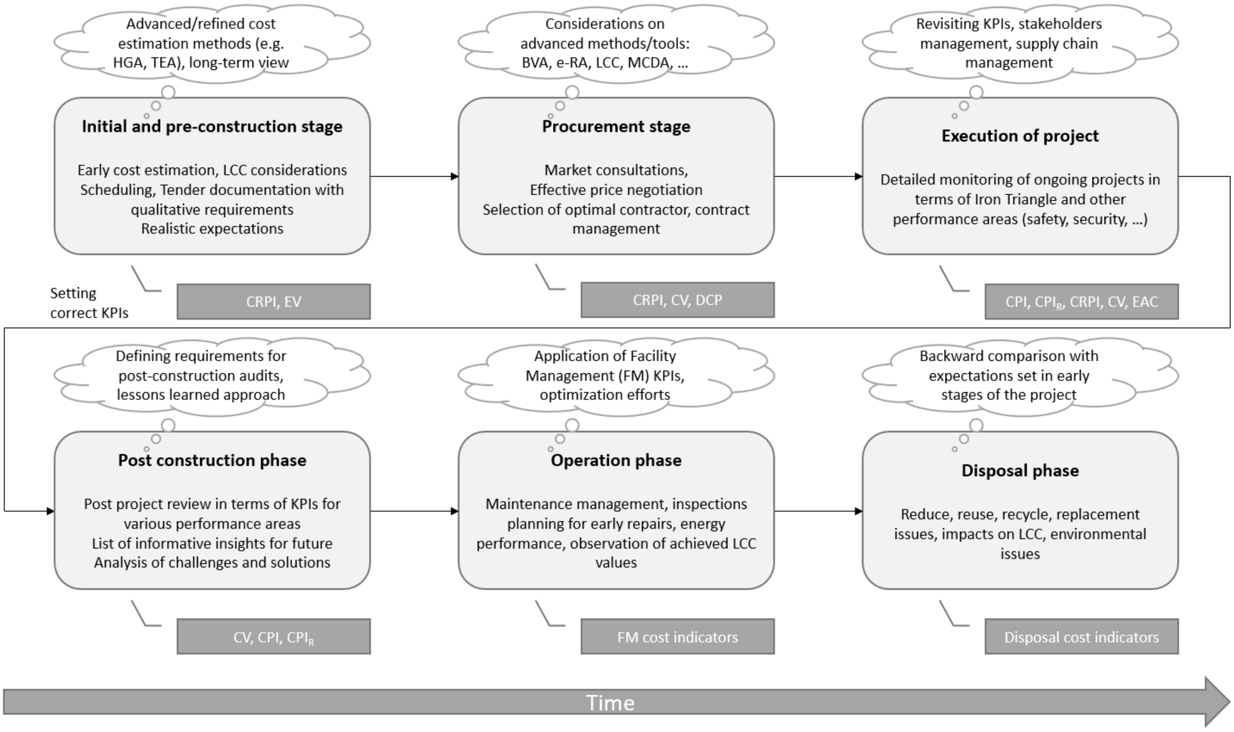

Figure 8. Scheme of selected key economic prospects for further development of performance management systems

4 CONCLUSION

The presented work accentuates persistent debate in construction and project management literature and actual practice about how to measure performance and what determines the success of a project. Advanced performance management is necessary to steer the project during any of its stages. Performance measurement systems should therefore build on the "Iron Triangle" approach and its extensions to capture various aspects, features, challenges and evolving areas of the construction industry.

Recent developments in this research area provide promising outputs in relation to the assembly of a dynamic and holistic performance management system. The further adoption of advanced systems by practitioners will require them to move beyond their comfort zone, away from the traditional concepts, to adapt their mindset and make changes to the established routines. Finally, the follow-up initiatives should lead to a closer interconnection of the project and organizational levels of performance. The field of "*Civil Engineering Management*" connects technical, economic and managerial disciplines. Therefore, any further development of performance management models and particular measurement metrics requires an interdisciplinary approach across various construction specializations.

5 CONCEPT OF FUTURE ACTIVITIES IN RESEARCH AND TEACHING

The research activity will continue to be focused on business economics and performance management and measurement with an emphasis on the project level and economic aspects within the construction industry. The findings presented in the thesis enhance the call for improving existing measurement approaches by adding new dimensions. Indeed, the interaction of individual stakeholders in a construction project with respect to their individual goals and expectations will affect their performance, such as in the context of the emerging long-term perception of investors and prevailing short-term perception of suppliers.

It should be reiterated that the ongoing Covid-19 pandemic has significantly affected the national economy and the construction sector is no exception, especially in terms of disrupted supply chains and significant fluctuations in the prices of construction materials. Further research will therefore be directed especially towards LCC and sustainability, as well as supply chain management issues and their effect on performance.

The author plans to further develop the scope of international cooperation. A substantial part of the author's current research activities takes place at an international level (in cooperation with UPC BarcelonaTECH, University of Rijeka, University of Ljubljana, Cracow University of Technology and other institutions), also with the support of international projects. The constant effort to expand the professional and scientific collaborative networks have resulted in the recent involvement of new partners (RheinMain University of Applied Sciences and University of Natural Resources and Life Sciences in Vienna).

Regarding the pedagogical activity, research outputs are continuously passed on to the teaching process to keep students up to date with the latest trends and approaches in the field of Civil Engineering Management. An important task is to enable talented students to further develop their skills, either in the form of student competitions or through participation in specific research projects. At more advanced levels of study, emphasis must be placed on students' independent thinking and, regarding doctoral students in particular, also on getting prompt feedback from the international scientific community in the form of active participation in conferences and by being confronted with sound reviews by scholarly journals.

I consider it essential that the teaching process also includes the input of experts from the industry and from abroad, which will allow students to gain a better awareness of the subject matter they are being taught about. Therefore, I appreciate and actively make use of development and internationalization projects by which the university supports this kind of involvement. By maintaining and developing long-term good relations with foreign partners, I will also encourage and support the mobility of students to partner universities across Europe.

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CZECH ABSTRAKT (Shrnutí)

Předložené teze pojednávají o problematice měření a řízení výkonnosti ve stavebnictví z pohledu různých perspektiv, přičemž akcentují potřebu posunu od konvenčního přístupu k dynamickému pojetí zahrnujícímu celoživotní hledisko. Teze představují část výzkumné činnosti autora zaměřené na vybrané ekonomické a manažerské aspekty působící na výkonnost s akcentem na projektovou úroveň. V práci jsou postupně představena základní hlediska a vybrané klíčové indikátory výkonnosti stavebních projektů, na které volně navazuje problematika řízení výkonnosti na úrovni organizace. Pozornost je věnována především ekonomickým indikátorům, umožňujícím řídit výkonnost projektu / stavebního díla v rámci celého jeho životního cyklu. S ohledem na projektově-orientovaných charakter stavebnictví a velký počet účastníků projektu, práce také pojednává o teoretických východiscích a praktických aspektech týkajících se přístupu ke stakeholderům.

Prezentované výstupy poukazují na potřebu rozšíření záběru stávajících systémů řízení výkonnosti založených na principu „Iron Triangle“ (projektového trojimperativu neboli železného trojúhelníku) o další oblasti kontroly, například obstarávání, odhady / kalkulace nákladů a stanovování nabídkových cen, problematiku udržitelnosti z pohledu nákladů životního cyklu, řízení dodavatelského řetězce a dopadů na životní prostředí, potřebu sledování rizik a zohlednění principů teorie stakeholderů.

Výstupy vědecké činnosti potvrzují přetrvávající nejednoznačnost stanovení předpokladů úspěchu stavebního projektu a odbornou debatu o tom, jak vlastně měřit výkonnost. Teze přinášejí výhledy na další směřování vědecko-výzkumné činnosti v oblasti měření a řízení výkonnosti ve stavebnictví s důrazem na schopnost nastavovat adekvátní a realistické výkonnostní cíle a schopnost dynamicky sledovat výkonnost projektu holistickým přístupem. Další rozvoj systémů měření výkonnosti by měl podporovat schopnost predikce ve vazbě na dosahování vytyčených cílů a využívat pokroků dosažených v rámci stále se rozvíjející digitalizace stavebnictví.