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Evaluating the effectiveness of cyber-physical systems and technologies in the construction complex

Evaluación de la eficacia de los sistemas y tecnologías ciberfísicos en el complejo de la construcción

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ABSTRACT

The problem of optimization of construction at all stages of the life cycle of a construction object is one of the most significant. The solution to this problem is the introduction of cyber-physical systems and technologies. The issues of introducing digital tools in construction have been of long-term interest to both researchers and practitioners, since these processes provide construction companies with additional economic benefits, reduce lead times and improve the quality of finished construction products. The article defines the main types of cyber-physical systems and technologies that have the potential for development the economy in the context of digitalization, identifies the main problems of introducing digital tools by small construction enterprises, systematizes and groups indicators for evaluating the effectiveness of their implementation. The authors propose three groups of performance indicators, including performance indicators of construction processes at the stages of the life cycle, performance indicators for the implementation of a construction process management system based on information systems and technologies, performance evaluation indicators for the implementation of investment projects for the implementation of cyber-physical systems and technologies in construction. The results of the study can be used to develop recommendations for improving the efficiency of construction processes based on the introduction of cyber-physical systems and technologies.

Keywords: construction, cyber-physical systems and technologies, BIM, technologies of information modeling, efficiency, return on investment.

RESUMEN

El problema de la optimización de la construcción en todas las etapas del ciclo de vida de un objeto de construcción es uno de los más significativos. La solución a este problema es la introducción de tecnologías y sistemas ciberfísicos. Los problemas de la introducción de herramientas digitales en la construcción han sido de interés a largo plazo tanto para los investigadores como para los profesionales, ya que estos procesos brindan a las empresas constructoras beneficios económicos adicionales, reducen los plazos de entrega y mejoran la calidad de los productos de construcción terminados. El artículo define los principales tipos de sistemas y tecnologías ciberfísicos que tienen potencial para el desarrollo de la economía en el contexto de la digitalización, identifica los principales problemas de la introducción de herramientas digitales por parte de las pequeñas empresas de construcción, sistematiza y agrupa indicadores para evaluar la efectividad de sus implementación. Los autores proponen tres grupos de indicadores de desempeño, que incluyen indicadores de desempeño de los procesos de construcción en las etapas del ciclo de vida, indicadores de desempeño para la implementación de un sistema de gestión de procesos de construcción basado en sistemas y tecnologías de la información, indicadores de evaluación del desempeño para la implementación de proyectos de inversión. para la implementación de sistemas y tecnologías ciberfísicas en la construcción. Los resultados del estudio se pueden utilizar para desarrollar recomendaciones para mejorar la eficiencia de los procesos de construcción basados en la introducción de tecnologías y sistemas ciberfísicos.

Palabras claves: construcción, sistemas y tecnologías ciberfísicas, BIM, tecnologías de modelado de la información, eficiencia, retorno de la inversión.

1. INTRODUCTION

Information modeling of construction processes is currently one of the most urgent tasks for modern construction enterprises. According to the Russian national portal of draft regulations (Russian national portal of draft regulations, n.d.), a draft Decree of the Government of Russia has been developed, which provides a list of objects for the mandatory implementation of information modeling. In particular, maintaining an information model for construction projects under government orders is mandatory. Thus, construction organizations should be ready to introduce cyber-physical systems and technologies into production processes right now.

There is a need for scientific developments, new ideas, research, analysis of foreign experience in this area, which will make it possible to most fully represent the direction of development of the Russian construction industry, assess risks and use the opportunities provided by information modeling technology, choose tools that are characterized by the optimal ratio of economic costs and the result obtained.

An analysis of the scientific base in the field of cyber-physical systems and technologies showed a significant interest of researchers in this problem, including both from the standpoint of conducting broad reviews of research and for solving highly specialized problems.

This is also noted by a number of researchers, such as Lopez, Lerones & Lamas (2018), who set the task of researching the identification of the most significant publications, the evolution of interest in the topic of building modeling with a view to their subsequent reconstruction or new construction. According to their research, the combination of new data acquisition technologies based on methods such as photogrammetry, terrestrial TLS laser scanning, point cloud method, semi-automatic and automatic modeling are the most interesting.

Photogrammetry is an accurate non-contact 3D measurement technique based on multiple high-quality images to accelerate the collection of semantic and spatial data of a building or object (El-Hakim et al., 2007; López et al., 2018).

The widespread use of photogrammetry methods in the creation of maps and plans, as well as for their correction, makes it possible to speed up the deadlines for completing tasks related to land management and cadastres and significantly improve the quality of cartographic materials, in addition, it makes it possible to automate a number of labor-intensive processes in these areas (Khabarova et al., 2019; Głowacki et al., 2016).

However, ordinary photogrammetry does not allow you to make high-quality 3D models, since its result needs to be corrected. The authors Reizgevičius, et al. (2018) compare photogrammetry and computer vision algorithms, concluding that the best result will be obtained by combining these two methods and creating digital photogrammetry.

Terrestrial laser scanning technique is the most efficient, high-performance tool of obtaining accurate, and most complete information about a spatial object: an architectural monument, a building and a structure. The essence of ground laser scanning is to determine the spatial coordinates of the object's points. The process is implemented by measuring the distance to all determined points using a phase or pulsed reflectorless range finder (Barazzetti et al., 2019). The technique is widely used in the construction of new facilities and reconstruction. The effectiveness of this method depends not only on the quality of scanning, but also on how well the results are processed and interpreted. The use of this technique is being explored by scientists such as Tsakiri, & Anagnostopoulos (2015), Saha et al. (2021), Calin et al. (2015), Glowacki et al. (2016), Brazzetti et al. (2019).

The point cloud method is to use remote sensing tools at the construction site and evaluate it using metrics. The Bassie method (Bassier et al., 2019) evaluates the quality of construction of objects through various metrics and taking into account the vectors of systematic errors.

The use of this method will improve the quality of building objects models by reducing the number of errors in the process of processing scanning results.

TIM (building information modeling technology) or BIM (building information modeling) exists to solve problems associated with building information management methods. Although it can be said that TIM is a technique that uses a 3D parametric modeling technique to consolidate information obtained during the construction phase into a database to facilitate links between data points. At present, it is mainly used for various evaluations and analyzes that use 3D models, such as interference evaluation, sunlight analysis, view area analysis, and energy analysis. That is, while BIM is effectively used for analysis using 3D models, it is not used for managing building information by consolidating building information and creating databases. This may be due to the insufficiency of database systems for managing BIM information and the lack of means for effectively linking figure information and non-figure information.

The BIM methodology is mostly used at the design stage of buildings. For example, researchers Ding et al. (2019) have proposed a digital building framework that integrates building information modeling (BIM) and reverse engineering (RE) to improve the use of information at different stages and thus reduce errors and rework in renovation projects during urban renewal. Three-dimensional (3D) laser scanning is used to enable the RE process. Implementation of this proposed scheme at sites in China allowed to optimize the reconstruction process by 15%, eliminate design changes by 30% and rework by 25%, and finally save two months and 7.41% of steel construction costs.

The use of BIM technologies is important not only for housing construction, but also for the construction of supporting infrastructure facilities, such as transport. Thus, researchers Costin et al. (2018) made an attempt to classify scientific and practical approaches to the study of digital tools for designing transport infrastructure.

These technologies are now actively used in construction.

According to ISSEK HSE research (Abdrakhmanova et al., 2021), the prospect of digital transformation of the construction industry is based on the use of virtual and augmented reality (VR/AR), artificial intelligence, wireless communication technologies and new production technologies. The volume of demand for modern digital technologies in construction will grow to 296.7 billion rubles by 2030. from 14.9 billion rubles in 2020.

A review of scientific research and practical reports creates a false impression that the study of the problem of the use of information technology in construction has already been exhausted, markets for its application and the legislative framework have been formed.

However, new actors, such as investors and operating organizations, are actively involved in the construction digitalization process. In this regard, issues related to evaluating the effectiveness of the introduction of digital technologies remain relevant and need further research.

2. METHODOLOGY

According to the Ministry of Construction of Russia, in 2020 only 7% of construction companies in Russia used BIM technologies, and by 2022 their number has grown slightly. Digital technologies are being used in large cities for the implementation of large projects. Small regional companies use such instruments only when they participate in government contracts. The government sets the task of fully switching to digital technologies for managing capital construction by 2024.

According to the National BIM Report (2019), 51% of construction companies say that digitalization makes the construction process more costly.

The main costs of the company in this case are:

- Technology implementation costs,

- Training costs,

- Expenses for internal expertise,

- Costs of approval.

A survey of 10 small and medium-sized companies working in the construction industry in the Penza region, Russia, (design organizations, construction and installation organizations) showed that companies can use certain digital tools, for example, 3d scanning, the use of specialized software for design activities. But they did not even try to calculate the economic efficiency of the integrated introduction of BIM technologies into construction processes.

The reasons given were:

- Lack of initial data for calculations;

- Non-obvious expediency of changes at individual stages of the life cycle of a building product;

- Lack of understanding of the methods of linking information technologies at the stages of the life cycle into a common system in combination with the rest of the participants in the construction process;

- Misunderstanding of methods for calculating the effectiveness of information technology implementation;

- Resistance to change in the presence of well-functioning production processes.

3. RESULTS AND DISCUSSION

The result of the work will be a balanced schedule for the production of works, taking into account the schedule for the supply and installation of process equipment. Balanced demand schedule for materials, people, machines and mechanisms. On-site construction support, ensuring, in the event of deviations during the implementation of the Project, the adoption of effective operational organizational and technological solutions to keep the Project within the target indicators is specified depending on the needs of the customer. The effectiveness of digital technologies implementation in construction processes can be calculated based on **three** groups of indicators.

1. The first group of indicators includes the effects associated with the optimization of construction processes at all stages of the life cycle, from design to commissioning of construction facilities.
Today, in 80% of cases, BIM technology (2020) is implemented at the design stage of a real estate object, in 15% it is used at the construction stage, and only in 5% during the operation of the facility. Despite this, the effects arising from the implementation of a construction project are formed mainly at the construction stage as a result of optimizing the design processes and ensuring the organization of production.
Reducing production losses based on BIM modeling will occur due to:

Reducing the material consumption of work due to the accurate selection of materials and resources;
Optimizing the use of production equipment.

Optimization of the scope of work, including reduction of additional volumes by improving the quality, completeness and accuracy of project documentation, its coordination at all stages, access to a common database of all project work, the introduction of digital twins.

Reducing non-production losses in the design and implementation of a construction project will be achieved through:

- Improving the accuracy of calculating the physical volume of work (using verified BIM models);

- Moving from top-down planning to bottom-up modeling;

- An optimized way to implement the project based on calculations, taking into account the available opportunities and constraints (time, cost, volume, structure, climate, logistics, resource base, external economic environment);

- Detailing work to work processes, which will ensure the transition from the standards of enlarged types of work to technologically sound standards;

- Ensuring a balanced use of labor resources, which will reduce the number of emergency calls and downtime.

- Making optimal and informed decisions throughout the project.

The reduction of losses during the operation phase will occur due to the integration of databases, project documentation, three-dimensional models, maintenance procedures and sensor indicators. Thus, the implemented monitoring system can integrate data on objects not only at the level of a building or a residential complex, but also at the level of a district or an entire city. In the long term, this can provide effects at the macro level.

The use of BIM technologies will reduce the probability of errors and inaccuracies in project documentation by up to 40% in comparison with traditional design methods, reduce the time for project development by 20–50%, reduce the time for its verification by 6 times, and reduce the time for coordination and approval by up to 90%. According to the Higher School of Economics, more than 60% of Russian construction organizations note improved understanding of the project by all participants, higher project quality, information availability, fast data transfer and information exchange among the main effects of the implementation of BIM. In 81% of organizations, the effect of using BIM, actually obtained during the work with projects, exceeded expectations (Asatryan et al., 2019).

A successful example of improving construction efficiency is the Bergen S-Bahn expansion project in Norway. Modeling of the object and the area around it was carried out. BIM tools helped 18 companies from five different countries to coordinate the process, reducing construction costs by 25% from originally planned.

2. The second group of indicators is based on the assessment of the effectiveness of the construction process management system based on the use of information systems and technologies.

An important factor affecting the efficiency of construction process management using information technology tools is the design and implementation of a process management system.

The core of the system can be a Construction Progress Monitoring Center, which collects up-to-date information from the construction site with reference to simulation models, manages a remote construction site, plans and monitors the performance of weekly and daily tasks based on simulation models.

Cost and resource efficiency indicators are influenced by parameters such as speed, quality, cost and technology. They should be taken into account when forming a parametric model of the effectiveness of the management system in construction.

The choice of these parameters and criteria is explained by the desire to characterize the process on a multilateral basis.

Based on (Kochetkova, Gorinova, 2013) Parametric model of the process efficiency management system in construction is developed (table 1).

Table 1. Parametric model of the process efficiency management system in construction

<table>
<tr><td colspan="2" rowspan="2">Process performance criteria</td><td colspan="4">Process parameters</td></tr>
<tr><td>Speed (S)</td><td>Value (V)</td><td>Quality (Q)</td><td>Technology (T)</td></tr>
<tr><td rowspan="2">I Management performance evaluation indicators (M)</td><td>Management performance indicators</td><td rowspan="2">Group MS</td><td rowspan="2">Group MV</td><td rowspan="2">Group MQ</td><td rowspan="2">Group MT</td></tr>
<tr><td>Human resource management performance indicators</td></tr>
<tr><td rowspan="4">II Resource management performance indicators (R)</td><td>Indicators of the material resource efficiency</td><td rowspan="4">Group RS</td><td rowspan="4">Group RV</td><td rowspan="4">Group RQ</td><td rowspan="4">Group RT</td></tr>
<tr><td>Indicators of the intellectual resource efficiency</td></tr>
<tr><td>Indicators of the finance resource efficiency</td></tr>
<tr><td>Indicators of the information resource efficiency</td></tr>
</table>

III Indicators of object environment management (E)	Indicators of the external management environment development	Group ES	Group EV	Group EQ	Group ET
	Indicators of the internal management environment development				
IV Management process evaluation indicators (P)	Procurement Process Performance Indicators	Group PS	Group PV	Group PQ	Group PT
	Manufacturing Process Performance Indicators				
	Logistics Process Performance Indicators				
	Sales process performance indicators				

In all groups (MS, MV, etc.), a number of indicators are determined that take into account the normative values for the main characteristics of the reengineering of the main processes in construction.

A practical approach to the formation of a project progress monitoring center can be based on the technology described below.

As operational information from the construction site, two technologies have become the most widespread: the use of optical scanners on an unmanned aerial vehicle (UAV) and a BRIO MRS tablet with mixed and advanced mixed reality technology.

The use of UAVs has proved most effective at areal sites where a large amount of excavation work takes place. The construction control engineer can provide up-to-date information on the actual earthworks performed on a daily basis.

Figure 1. The use of optical scanners on an unmanned aerial vehicle (UAV)

The BRIO MRS tablet proved to be the most effective in complex engineering objects with a large intersection of communications. This technology allows you to visualize the information model directly on the construction site. The building control engineer must mark the object to be installed and compare with what is to be built. If a violation is detected, the order is issued directly to the mounted element. At the end of the working day, an order is issued to the contract contractor (Kharisov et al., 2022).

Figure 2. The BRIO MRS tablet

The BRIO MRS tablet is effective for complex engineering objects with a large intersection of communications

Having an information model on the site, it is possible to get all the embedded information, indicate the current status of the mounted element and transfer to the manager's desktop a 3D graph of the object, where the colors indicate: yellow - the element is mounted, red - the element is overdue, and green - the element is mounted and accepted technical customer.

When processing the information model, the technical customer is obliged to assemble the executive information model or the "as built" model, bring the graphical representation of the information model into line with the actual one, make adjustments to the information model, and actually indicate "as built". In addition to graphic display, the technical customer is obliged to enter into the information model all the information about the materials used, passports for equipment, certificates and other documents required by law.

At each stage of the construction project, each participating unit will generate relevant information into the project data through the digital platform and transmit the TIM data, and continuously enrich the data in the TIM database. For example, in the previous planning phase, the construction division analyzes the social, political and market environment in which the project is located through environmental surveys and analyzes the case for the project's scope, composition, function and evolution. It also builds a highly realistic virtual 3D visualization model in the virtual space, analyzing the safety factor of the design scheme, the validity of the structure layout and energy consumption.

TIM can compensate for the loss of information by allowing each team to complete and reference all the information they receive during the TIM model change period.

For example, the owner will be able to detect evidence and root causes of a leak in their building. Instead of analyzing the physical structure in the usual ways, he can turn to the model and see what potentially dangerous elements are in this area.

Thus, the construction management process is optimized, which will provide an economic effect.

Cost analysis can be automated using 5D Building Information Modeling (5D BIM). The methodological framework for cash flow analysis and project financing takes into account the types of contracts and costs for equipment, wages and materials. What-if scenarios are used to test proposed solutions (Abdrakhmanova et al., 2021).

3. The third group of indicators aims to evaluate the economic effect for a construction company from the purchase and implementation of an information system in production.

The key indicator of the third group is ROI - an indicator of return on investment. It is customary to rely on this indicator when making a decision on investing in any project.

A number of researchers have paid attention to the methodology for assessing the ROI indicator in building design. Currently, one of the most common methods is to use the Autodesk Revit ROI tool. According to Abakumov et al. (2017), the specificity of this tool is that the calculations are based on infrastructure, project and long-term investments. It should be noted that this approach is optimal for large projects, while for a number of small companies, for example, design companies or organizations performing specialized types of work, the use of this tool is complicated.

In this regard, the Bilenko et al. (2020) approach can be proposed to determine the effectiveness of introducing cyber-physical systems and technologies into production based on the ROI calculator.

According to this approach, two groups of indicators are compared: the costs associated with the implementation of cyber-physical systems, such as the purchase of specialized equipment, software, training, administrative costs, etc., and the amount of increase in income from the implementation of cyber-physical systems, received as a result of increased production productivity, the effect of increasing sales volume and price growth, the effect of optimizing production and technological processes.

The result of the calculations is the RoTIM indicator - return on investment in cyber-physical technologies (Return On Investment).

This approach is simple, flexible and adaptable to different forms of construction business. However, it is necessary to take into account the specifics of the production for the use of this tool.

So, this coefficient can be applied without changes for construction industry enterprises, since it already takes into account all the cost groups associated with production.

When using this coefficient for construction companies and design organizations, it is necessary to adjust the cost and income items.

$$RoTIM = (Rt - It) / It \times 100\%$$

RoTIM - return on investment in information technology in construction (cyber-physical systems and technologies) (Return On Investment)

Rt - the sum of the increase in revenue (income) from the introduction of technologies (Revenue)

It - the amount of investment in technology (Investment)

Based on the adapted ROI calculator tool (Bilenko et al., 2020), the effect of introducing cyber-physical systems and technologies into a non-residential building construction project was calculated.

For the implementation of the project, a digital system was purchased for three workplaces with a total cost of 66,000 euros, including implementation costs. The monthly increase in income from the implementation of the system amounted to 26,400 euros. The indicators are adjusted taking into account the coefficients of risk and potential by 5%.

The results obtained are shown in Table 2 and Figure 3.

Table 2. Performance indicators of the project of cyber-physical systems and technologiesin construction

№	Indicators	Meaning
1.	Costs (investments)	€ 69 300
2.	Income growth per month	€ 26 400
3.	Return on investment period, months	2,6
4.	ROI in the first year	357,1%

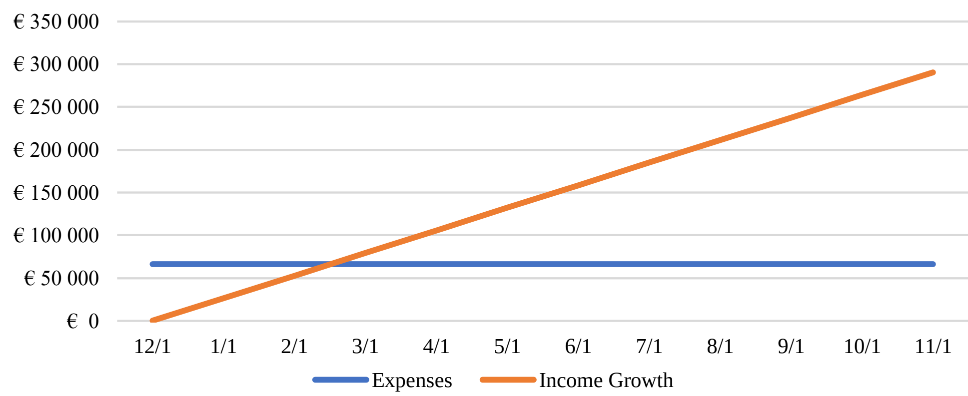

Figure 3. Return on investment period, months

Also, different scenarios for the implementation of various types of cyber-physical systems and technologies that differ in cost and efficiency were considered (Table 3).

Table 3. Scenarios of various projects for the implementation of cyber-physical systems and technologies in construction

	Scenario 1	Scenario 2	Scenario 3
Expenses	€ 48 510	€ 69 300	€ 124 740
Profit growth per year	€ 126 720	€ 316 800	€ 221 760
Return period	5	3	7
Profitability 1 year	161%	357%	78%

An obvious fact is the absence of a direct correlation between the cost of technology and the result. This fact is also reflected in Table 3.

These tools allow you to compare alternative project implementation options and choose the most effective one.

4. CONCLUSION

The paper summarizes the results of a scientific study on the problem of increasing the efficiency of construction based on the introduction of cyber-physical systems and technologies.

The analysis of scientific publications revealed a long-term significant interest of researchers in the implementation of information systems in construction in order to improve the quality of construction products and ensure the efficiency of construction processes from the standpoint of economics, organization and production technology. This led to the presence of a large number of approaches to the classification of information systems and technologies in construction.

Despite the considerable attention of researchers to this problem, the practical application of information technology in construction has significant growth potential. New areas of research are identified in the context of modern economic and technological trends.

The introduction of cyber-physical systems and technologies in construction provides the enterprise with a number of economic effects that are subject to a preliminary assessment in order to identify the most optimal implementation option.

The effectiveness of the implementation of cyber-physical systems and technologies is ensured at all stages of the life cycle of a construction object and is assessed on the basis of three groups of indicators: efficiency by reducing production and non-production costs at the stages of design, construction and operation of construction objects; efficiency of the implementation of a construction process management system based on digital technologies; efficiency of investments in the project for the implementation of cyber-physical systems and technologies in the construction industry.

These indicators should be applied in complex, as this will provide a comprehensive assessment of various options for the development of construction production and the effective implementation of digital technologies in construction, as well as create a basis for developing recommendations for improving the efficiency of organizing construction production in the current conditions.

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