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Research paper

The initial prototype BIM system for the optimization of integrated construction processes

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Abstract: It is often spoken and written about the use and benefits of BIM in the design, build, and exploitation phases. Based on an extensive analysis of scientific articles and practice, it has been noticed that, however, there is no comprehensive solution for the use of BIM at the stage of preparation for construction. And there is no relevant approach to the organization of construction though various software offers availability to calculate separate processes that are important for the organization of it. For example, based on the BIM model, determine the optimal place for the tower crane. But the problem is that such a local solution does not represent a comprehensive approach and does not represent apprehensive construction planning. It means, currently there is no method of planning, which will answer the questions: whether to choose a tower crane or a truck crane, where is the optimal place for unloading construction materials, considering the location of the crane, etc. Therefore, this article presents the vision and strategy of BIM development at the construction stage. The problem that should be solved now is the creation the strategy that will allow to improve the efficiency of construction works, adjusting them to the current situation in an optimal way. Therefore, the aim of the article is to combine separate ideas of BIM using in construction management as a whole and call scientists to discuss and supplement the topics of using BIM in construction management.

Keywords: BIM, construction management, extended reality, integrated construction process, mathematical model, optimization

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1. Introduction

In each construction, technological processes are implemented in exceptional, repeated conditions. Construction is characterized by technological processes that are not used in other sectors of industry. As a result, there are significant differences from other branches of the industrial economy [4, 10]. The main features of the construction sector are: (1) unique construction technology, (2) high fragmentation of products, materials used on the construction site, (3) installation of temporary infrastructure, (4) dependence on seasonality, weather conditions, (5) different sizes and weights of objects or elements under construction, (6) long service life of the facilities, (7) unpredictable duration of technological processes.

Based on the key features of the construction industry mentioned above, we can clearly state that the management and organization of construction are more complicated than in the case of other industrial sectors [6, 15], which dominate invariably and with the possibility of planning the process. BIM was used as a connection between an enterprise resource planning information system that handles information about the production process and construction objects, mainly supported by CAD tools. BIM project management processes at the construction stage have been explained in studies. BIM-based technologies can be strongly beneficial for construction site management through platforms collecting data and providing analytics [12, 13]. The utilization of Building Information Modeling (BIM) has been growing significantly and translating into the support of various tasks within the construction industry. The extent of the effectiveness of real-time communication within the BIM environment is somehow restrained due to the limited sense of immersion into virtual environments [17, 18]. Construction safety management has been a popular issue in research and practice in recent years due to the high accident and death rates in the construction industry. The complexity and variability of construction sites make safety management more difficult to implement than in other industries. As a promising technology, visualization has been extensively explored to aid construction safety management. MEP (Mechanical, Electrical, Plumbing) includes a vast amount of equipment types and pipelines in the integrated design, leading the coordination of MEP design optimization a major challenge for complex buildings. The article [9, 12, 14] presents a BIM – based integrated scheduling approach which facilitates the automatic generation of optimized activity-level construction schedules for building projects under resource constraints, by achieving an in-depth integration of BIM product models with work package information, process simulations, and optimization algorithms. Taking into account the issues related to feasibility already at the design stage may result in the improvement of the construction efficiency, saving of time and money, thanks to the smooth project execution [5].

2. Research methods

The construction site planning process is not identical for each construction. That is why there is a need to create an integrated system that optimizes building processes. To resolve the problems of construction technology organization and planning process, in this article the following methods are used: an integrated system of building processes optimization is being created, which includes overviewed literature of tools and methods to organize a construction site, and a system of implementation of scheme description. The methods and innovativeness of the system can be defined as:

Automated object visualization process. With the help of photogrammetry of the existing plot, models of buildings, networks, and other existing facilities will be identified and created in details. The received information will be current, in contrast to the information received from the archives. The scanned information will be transformed in an automated way into a cloud of points that can be used in design and further stages of the construction organization.

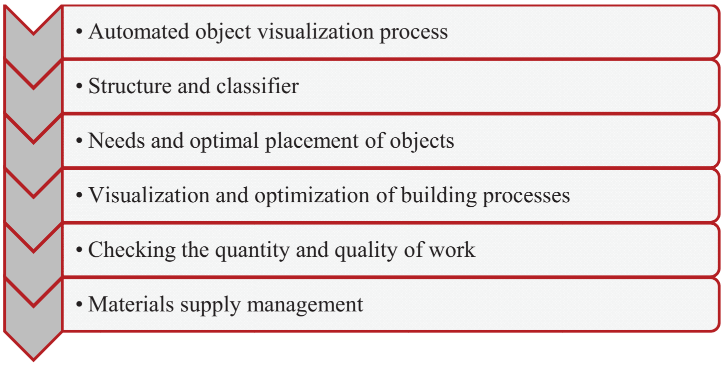

Fig. 1. Innovativeness of the system

The development of a company's structure and classifier allows an appropriate adaptation of equipment planning, mechanisms, and other resources in concordance with the company's capabilities. Therefore, the machines and equipment owned by the construction company will be modelled and transformed into a building plot model to use on the construction site in the first place, to substitute the equipment that would have to be rented from other enterprises. Determining the needs and optimal placement of objects on the construction site will allow an effective use of free spaces on the construction site as well as in an integrated and optimal way to locate objects on it. Visualization and optimization of building processes will help check the collisions of planned objects and enable an easier understanding of the construction organization. Checking the quantity and quality of work will allow to track the progress efficiently and quality of work carried out remotely, as well as perform automated invoicing of completed works. The management of building materials in the field of supply and storage and human resources will enable the use of artificial intelligence, which would not only track changes in materials and the location of human resources but also in an integrated manner would present management proposals and various simulations, for example, increasing the supply of materials and increasing human resources as well as the order of works (after the change), which will result in the appropriate stage of work being completed much faster.

3. An integrated system of building processes optimization

As part of the system, three basic elements were identified. The first is to create an automatic generation system of bid documents that involves executing, calculation of quantities, costing, schedules, and integrated work time management as well as the structure classifier of the company.

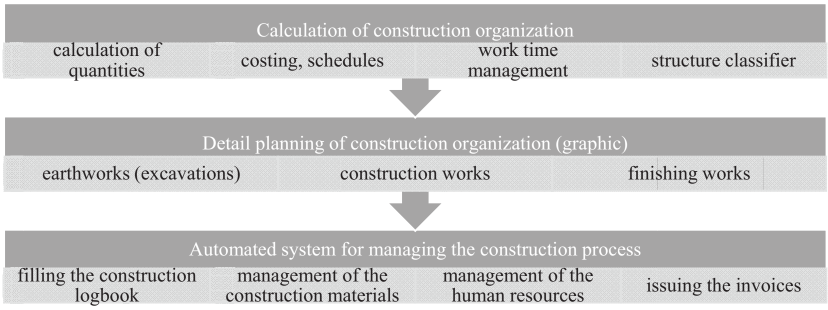

Fig. 2. An integrated system of building processes optimization

The second element within the framework of the project is the construction organization with an automated system that manages the detailed design documentation of the construction organization, which includes: the development of the construction site for the time of earthworks (excavations), construction works and finishing works. The forms of the results of the computational and descriptive and graphic parts, as well as the automatic construction of the schedule and cost estimate for the development of the construction site, will be developed. A tower crane planning in the pre-construction phase has long-lasting impacts on a project cost and schedule. Current approaches and tools being used by industry to facilitate a tower crane planning can be time-consuming, difficult to disclose all constraints, and challenging in visualizing and comprehending alternatives [7, 16]. Adopting Building Information Modelling (BIM) in Building Performance Analysis (BPA) is becoming an emerging research area in the application of information technology in the Architecture, Engineering, and Construction (AEC) industry. The integration of artificial intelligence activities in software development processes often arises [15]. Models with extended building information are the most advanced technology in the construction industry. Therefore, there is a need to create an IT system to optimize integrated building processes in an augmented reality environment. One way to obtain a model with extended information about the building can use the photogrammetry method. Architectural photogrammetry is one of the main ways to determine the shape, size, spatial position and study the qualitative features of various architectural and urban objects by non-contact determination of object coordinates and based on the reproduction of the object model using a stereo pair, i.e. at least two pictures of the object, obtained from different points in space. An important quality of photogrammetric materials is the ability to efficiently process them using a computer and software. The main tasks of photogrammetry are:

measurements and reviews of architectural structures; establishing architectural and urban monuments; structure displacement monitoring; preparation of documents based on aerial and ground photography, used as the basis for urban planning, topographic maps, data for geographical information systems.

The achieved results will enable the implementation of the third element, called the automated system for managing the construction process, which will analyze the quantity and quality of work, complete the electronic construction logbook, facilitate the management of the construction materials and human resources, as well as issuing the invoices.

4. Basic stages of automated system for managing the construction process

To achieve the set aim of the article – to combine separate topics about BIM using in construction management as a whole – it must be created a prototype of a new product, it means, IT system for optimization of integrated construction processes. This will be achieved by the creation of mathematical optimization models for the main stages of the construction process. The following steps for the system developing are intended to be useful for understanding and researching the current situation in the construction process, risk management, supervising the construction process, production engineering as well as the progress of works. Also, it helps construction management to identify available human resources and area needs, not only based on the schedule. Algorithms, based on the models, will be developed to enable the creation of a prototype of software (Fig. 3).

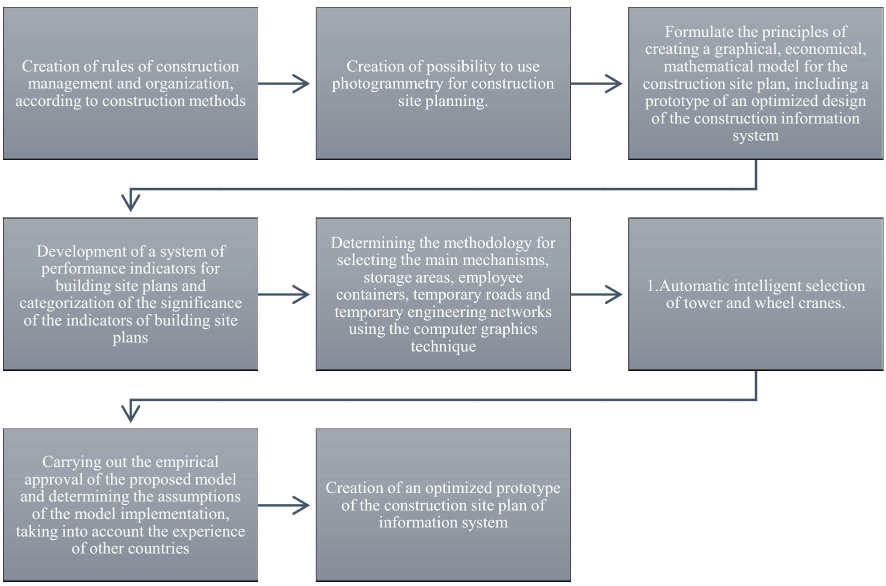

Fig. 3. Algorithm to enable the creation of a prototype of software

The construction management process is complex and consists of basic functionalities of the system – tendering of constructions works, construction process organization, management of construction process stages. In the tendering of construction works stage it intends to conduct development of work related to combining and shaping the currently available knowledge and skills in the field of science on photogrammetry technologies, business decision support systems, artificial intelligence, and indoor navigation (Fig. 4).

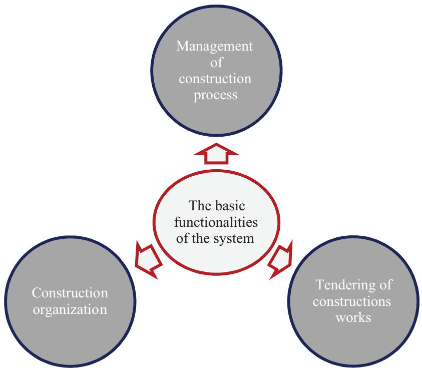

Fig. 4. Algorithm to enable the creation of a prototype of software

Automated system for the generation of execution of offered documentation contains calculation of the bill of quantities, development of the classifier structure, automated costing, automated construction scheduling, automated shift management. The second important stage is the organization of a construction process or automated system for the generation of executive documentation of the construction organization. At this stage, it is going to perform work based on extended reality. Therefore, a basic model will be built using photogrammetry technology. Such a model gives the possibility to build a 3D model with the simultaneous option of determining the coordinates in each of the points of the model. This gives the basis to determine the distance between the set points of the model, the ability to determine the area within the given limits, the ability to determine the volume of selected elements of the model. This gives the opportunity to analyze thoroughly the construction plot and build on this basis the construction site model. The designed tool should make it possible to include, as wide as possible, the technological equipment of the construction site (given equipment catalog with prices/costs), i.e.: vertical and horizontal-vertical transport equipment (cranes), machines with changing positions and/or work fronts, access roads and communication routes within the construction site, near-yard storage of materials and/or prefabricates, nearby production facilities (concrete and mortar preparation points, reinforcements, carpentry workshops, locksmiths, etc.), building material storage and material construction warehouses, temporary buildings with sanitary-living and office spaces, work safety equipment and fire protection, installations: water and sewage, heating, electricity, compressed air, communication, and signaling devices, as well as construction site fencing on the given construction. The described construction process organization stage includes: (1) development of the construction site at the stage of earthworks (implementation of excavations), (2) development of the construction site at the stage of skeleton assembly work, (3) development of the construction site at the stage of finishing works, (4) development of the form of results (computational and descriptive part), (5) development of the form of results (graphic part), (6) automated construction of the construction site development schedule, (7) automated construction of the construction site development costing, (8) automated material supply chain, (9) optimization of the construction site development schedule. In the stage of automated system for management of construction process an application of extended reality (created using photogrammetry technology) will be made, considering the assessment of the current qualitative and quantitative situation of the construction site and the construction works carried out. This stage consists of the following (Fig. 5).

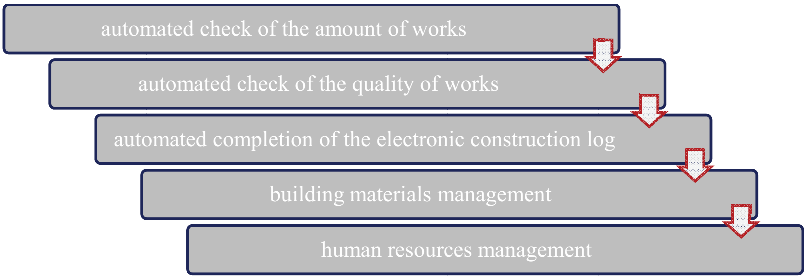

Fig. 5. The main stages of automated system for management

5. Research results – description of system implementation

It is well-known that these days mechanized processes dominate in the construction sector and require a variety of specialized mechanized techniques. Therefore, the strategic direction of the complex system described in this article also corresponds to reality. The developed system must be economically useful, reliable and must cover everything: rational, efficient planning of the entire construction site – machinery, equipment, storage areas, temporary buildings, temporary engineering networks, etc. As the construction process is continuous and repetitive with each new investment, the order, and specific stages in which the system should be integrated is described below (Fig. 6).

At the stage No. 1 – automation of take-off activities, tools will be prepared enabling full automation of take-off activities due to the fact that all building elements (structural or finishing) are included in the calculation in the form of take-off, material, and technological data. BIMestiMate is one of systems that uses a direct connection of the BIM model with data in the bill of quantities and vice versa. This allows automatic, intuitive, and accurate re-dimensioning of model elements (walls, floors, columns, foundations, etc.) with their simultaneous reflection in individual positions of the bill of quantities. The system also

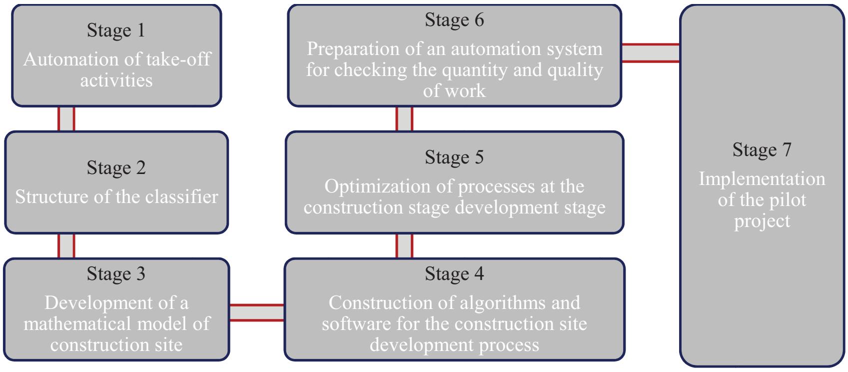

Fig. 6. Specific stages of system integration

eliminates errors in determining the number of works, which are the main reason for incorrect value determination, and significantly reduces the time needed to prepare the bill of quantities. New technology for building an object/objects model based on augmented reality will be developed. A classification system will be prepared that will offer a common basis for standardized, digitized information in the field of construction, operation, and maintenance to increase efficiency and productivity through improved information exchange. The indicated classification is needed primarily for data transference and management, ensuring complete information exchange; it is important to ensure that all items are sorted and selected using specific rules described in the international standard. Research and development related to combining and shaping the currently available knowledge in the field of science of holographic technologies and visualization systems of design solutions presented in BIM technology.

Stage No. 2. Structure of the company classifier. Based on the classifier, in the future, it will be possible to develop a system that automates the planning and management of construction production combining elements of information about materials (technical parameters), technologies associated with them, work consumption, etc. as well as costing, scheduling and changing of management. As part of the stage, industrial research will be carried out to develop the classifier system, which will be divided into the following elements: (1) classification of buildings, (2) classification of space, (3) functional systems classification – technical systems classification, (4) classification of components, (5) classification of properties, (6) classification of materials and aggregates. After developing the classifier system, work on automatic costing, scheduling, and change management will begin.

Stage No. 3. Development of a mathematical model of construction site development. The development of a mathematical model for the construction of the construction site for earthworks (excavation works), concrete works, assembly/execution of the structural skeleton and finishing works should enable the construction of the algorithm of the construction site development model at this time of works, and then the creation of software for the construction of the construction site for the stage earthworks, concrete works, assembly/execution of the structural skeleton and finishing works. The development of the mathematical model of the schedule together with the model of its optimization and costing for the stage of works during construction development should enable the construction of the schedule model algorithm for this stage of work together with the scheduling software.

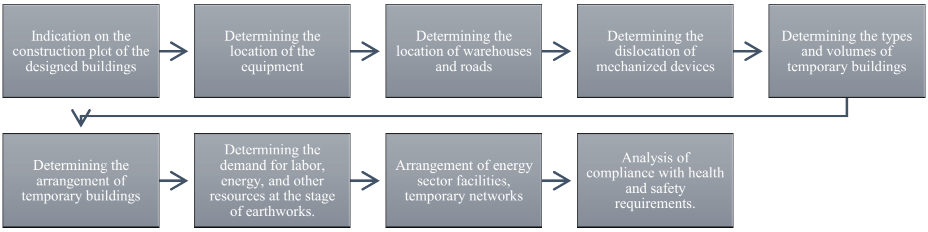

Fig. 7. Mathematical model of site construction for earthworks and concrete works

The provision of the materials to various construction sites may be different. A case of transporting the materials by motor vehicles is analysed below. In this case, the storage areas for materials should be planned first, followed by the ways of their delivery. The selection of the location of the storage areas and mechanisms (e.g. for making concrete and mortar) aimed at servicing several objects on the construction site is performed, taking into consideration the cost of transporting building materials, and is calculated as follows:

$$C = \sum_{i=1}^{n} c' Q_i L_i \tag{5.1}$$

c' – the costs of transporting one tonne of materials over the distance of one km; Q_i – the amount of materials needed for each object; L_i – the distance from the storage area or the location of mechanisms to the object; n – the number of objects.

Based on the assumption that the objects are spread over the construction site and using the Cartesian coordinate system, the distance from the storage area or mechanism location to the object and the costs of transportation can be calculated as follows:

$$L_i = \sqrt{(x - x_i)^2 + (y - y_i)^2} \tag{5.2}$$

$$C = \sum_{i=1}^{n} c' Q_i \sqrt{(x - x_i)^2 + (y - y_i)^2} \tag{5.3}$$

x and y are the coordinates of the location of each object, for which the distance to the storage area or the mechanism's location (Fig. 8), as well as the transport expenses, are the smallest.

The appropriate area for permanent objects is determined taking into consideration the location $x_1, y_1, \ldots, x_n, y_n$ of each object and minimizing the total expenses of the temporary

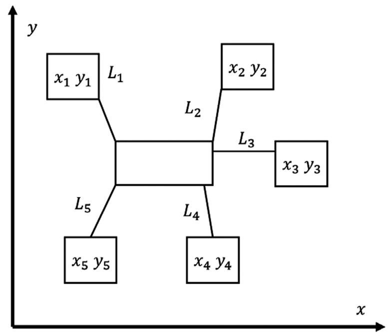

Fig. 8. The plan of selecting the locations of the objects

electric power systems and the time of the workers' movement on the construction site. Therefore,

$$L = \min\left(\sum L_{lV}C_{lV} + \sum L_{lN}C_{lN} + \sum L_{lS}C_{lS} + \sum L_{dJ}C_{dJ}\right) \tag{5.4}$$

L_{lV} is the length of the temporary water supply, sewage and heating systems and the movement of the workers on the construction site; $C_{lV,lN,lS,dJ}$ are the coefficients of expenses.

It is assumed that the areas planned for temporary buildings are on the construction site's territory and cannot be planned in the area of the constructed building. The distance between the objects should not be smaller than the approved one, K_{ij}:

$$K_{ij} \leq \sqrt{\left(X_{ij} - X_{(i+1),j}\right)^2 + \left(Y_{ij} - Y_{(i+1),j}\right)^2} \tag{5.5}$$

where K_{ij} is the admitted distance between the temporary buildings. X and Y are the coordinates of the location of each object, for which the distance to the storage area or the mechanism's location, as well as the transport expenses, are the smallest.

Stage No. 4. Construction of algorithms and software for the construction site development process. Construction of algorithms for the construction site development process at the stage of earthworks, concrete works, assembly works of the structural skeleton, calculation of the schedule with its optimization, and cost estimation should enable the creation of software for the construction site development at the above stages. The challenge will be to develop new software for a rational use of the construction site at the stage of earthworks based on augmented reality technology. Based on the mathematical model, an algorithm will be created for the construction site development model at the stage of earthworks, concrete works, implementation/assembly of the structural skeleton, and finishing works. Using the mathematical model of the BIM schedule, an algorithm will be developed for calculating the schedule along with its optimization, costing at the construction site development stage, taking into account the workload data (based on the company classifier), the number of works, resources and assumed productivity, taking into account various optimization strategies.

Stage No. 5. Optimization of processes at the construction stage development stage. The challenge will be to develop new software (creating catalogs, specifications, etc.) to calculate the demand for temporary objects, machines, and devices and temporary networks, then visualize them and create graphic libraries corresponding to the geometric parameters of individual objects available on the market. Using the mathematical model and the developed algorithm, software for cost of a construction site development and construction site planning will be created. Below it is presented short description about multiple criteria decision methods – COPRAS, TOPSIS and SAW. Three multiple criteria decision support methods based on quantitative measurements used to increase the reliability of the decision. The wide application of optimization methods is described in the following articles by the authors [1, 2, 18–20]. For optimization, it is used a multiple criteria complex proportional assessment of the projects method (COPRAS) [3]. The significance and priority, examined using this method, directly and proportionally depends on the system of criteria that adequately characterizes the alternatives, efficiency indicators, values, and their weights. The experts determine the system of criteria and calculate the criteria values and the initial significances. The groups of interest according to their goals and opportunities may adjust all this information. Also, alternative assessment results provide a detailed outline of the general original data of the experts and groups of interest:

$$Q_i = S_{+i} + \frac{S_{-\min} \cdot \sum\limits_{i=1}^{m} S_{-i}}{S_{-i} \cdot \sum\limits_{i=1}^{m} \dfrac{S_{-\min}}{S_{-i}}}, \qquad i = \overline{1,m} \tag{5.6}$$

the relative significance of the comparative options (efficiency) is determined by characterizing positive S_{+i} and negative S_{-i} features. The higher the Q_i, the higher the project efficiency. Another optimization method – simple additive weighting (SAW) method [8]. Simple additive weighting (SAW) is well known, the simplest and most widely applied. The normalized values are multiplied by significances and summed when determining the rationality of the option. the maximum sum of products shows the rational option

$$A = \left\{ A_i \left| \left| \frac{\sum\limits_{j=1}^{n} \overline{q}_j \overline{x}_{ij}}{\sum\limits_{j=1}^{n} \overline{q}_j} \right| \right. \right\} \tag{5.7}$$

here x_{ij} is normalized decision matrix.

Technique for Order Preference by Similarity to Ideal Solution method (TOPSIS). Yoon and Hwang (1981) developed the methodology based on the concept that the optimal alternative is at the minimum distance to the ideal solution and the greatest distance to the worst solution. this method is called the technique for order Preference by similarity to ideal solution method (TOPSIS). the relative distance of each (i) option to the ideal is determined:

$$K_i = \frac{L_i^-}{L_i^+ + L_i^-}, \quad i = \overline{1, m}, \quad \text{then } K_i \in [0;\ 1] \tag{5.8}$$

here L_i^+ is the distance between the comparative (i) and the ideal option. L_i^- is the distance between the comparative (i) and the worst option. the closer the K_i value is to 1, the closer the (i) option is to a^+, i.e., rational option will be the one that K_i value is the highest.

Stage No. 6. Preparation of an automation system for checking the quantity and quality of work. The challenge will be to prepare an automation system for checking the quantity and quality of work, for which a unique and easy-to-use module is needed, due to which a real work progress, and especially the amount of work performed, is compared with the design quantity and quality of the appropriate class of construction. Shapes, relationships, and new programs for creating electronic construction logs, automatic management of building materials, and human resources as well as invoicing for successive stages of construction works will also be developed. Automatic procedures will be developed for checking the quantity and quality of construction work. For this purpose, photogrammetry and artificial intelligence models will be used where development of image algorithmizing and determination of the quantity and quality of work performed will take place. The next goal is to develop a data transfer system from photogrammetric models and a fault management system to the electronic construction log. They should be inventoried, properly described, and qualified according to their validity and monitored until they are removed. The fault management system is a solution supporting the quality system. Based on the construction site development plan and construction site development schedule as well as the cost estimate, the control of the supply of building materials, and the human resources management process should take place. In the event of deviations from the planned situation, a correction process is foreseen in the time and schedule of construction site development. Based on the electronic construction log data, invoicing is carried out using the company's existing tools for which appropriate interfaces should be developed.

Stage No. 7. Implementation of the pilot project. The challenge will be to make a pilot project considering the classification in the areas of take-off, costing, and scheduling as well as change management. The implementation of the application of the automatic system for the generation of executive documentation will be implemented for the stages of earthworks, concrete works, assembly works, finishing works with the possibility of building a schedule and cost estimate for the construction of the construction site, including the classifier. The challenge will be the implementation of take-off applications, automated checking of the amount of work, checking the quality of work, building an electronic construction log, building materials management, human resource management, invoicing considering classification. As a part of this stage of work performed in the Project, development work will be carried out to fulfil a pilot project considering the classification in the areas of take-off, costing, and scheduling as well as change management. An automated system for the formation of executive documentation of a construction organization will be implemented. As part of the stage, development works will be carried out to carry out the pilot project using automated checking of the amount of work, checking the quality of work, construction of the electronic construction log, building materials management, human resources management, invoicing considering classification.

6. Discussion of the expected functionality

As mentioned before, this article presents not only the vision and strategy of BIM development at the construction, especially construction management stage, using virtual reality, but it also one of purpose – to call scientists to discussion and to supplement separate topics of using BIM in construction management. Combined separate topics about BIM use in construction management provide an opportunity to create a complex system. Predictable features (functionalities) of the system result, benefits (advantages), technical parameters are given in Fig. 9, which need to be expanded and further improved.

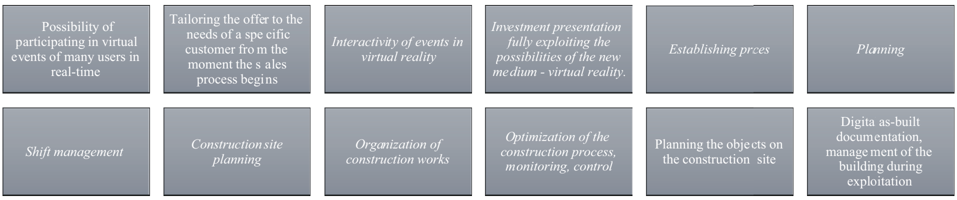

Fig. 9. Predictable functionalities of the system

7. Conclusions

Based on the analysis of the literature and the real situation in construction, it can be argued that BIM technology is not sufficiently used in the management process. It should be noted that there are separate computer programs for solving individual management tasks. There is a real need to create a comprehensive computer system to solve the problems of organization and management in construction. A detailed analysis of the literature has shown that due to the large number of variables associated with the construction site model, the assumptions and possibilities are significantly different, but the general research aspects in the analyzed methods that define the plan for the construction site design have been identified. During the analysis of the software, it was found that there is no separate software developed that combines and allows an automated selection of all machinery and equipment on the construction site in one platform. The developed plug-ins allow to create a program code, which is used for automated selection of mechanisms, optimization of selected mechanisms, but the mentioned plug-ins are not properly integrated into all software of design and construction organization. It has been established that the research work performed is continuous, as the developed optimized prototype of the construction site plan information system is general and intended for the main stage of construction works – for the installation phase of the above-ground structures. For optimization and automatic modeling of site planning, selection of mechanisms, equipment and other temporary objects, it is necessary to integrate into the existing prototype of the information system and other stages of construction – earthworks, zero cycle construction, engineering networks and communications, environmental management, etc. At the bidding stage, it is necessary to analyze automatically the project proposed for construction, identify and, if it is possible, eliminate errors and inaccuracies in the project, determine the amount of construction works, prepare a cost estimate and construction schedule. At the stage of organization of construction, it is necessary to design automatically a construction plot at various stages of construction (excavation, foundation, construction skeleton, finishing, and special works). At the construction management stage, the quality and quantity of work should be automated for control, an automated construction log should be kept. Based on these activities, one must issue invoices for the work automatically. It is very important to use extended reality technology, for example, photogrammetry. This will help to assess the quality and quantity of work performed qualitatively and prepare executive documentation for commissioning the facility. The development of a comprehensive mathematical model, algorithm, and software will significantly improve the quality of the solution in the organization and management of the construction process.

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