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Metaheuristic Optimization for Efficient Construction Management of Building Projects

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Abstract. Effective management of production systems in the construction industry requires a complex solution of organizational and technical problems related to the coordination of heterogeneous optimization criteria performance. The primary impediment to real estate development is the complexity of making informed management decisions. Conflicting interests among various stakeholders can lead to disruptions in production processes and potential crisis situations. The aim of article is to explore the potential for adapting metaheuristic optimization methods on step of earthworks enhance intelligent construction management technologies. This will result in improving decision-making processes, optimize production workflows, increase productivity, and achieve strategic objectives. This research is inspired by the mechanisms of biological systems in nature. The innovation of the study described in the article lies in the development of an automated control algorithm based on metaheuristics, which broadens the application of digital information technologies across the stages of design, modeling, implementation of construction projects, and quality management of building operations. The result of the research allows us to optimize worker productivity during building construction. The high reliability of the models obtained clearly shows that metaheuristics can successfully improve construction processes and digital transformation can be effectively implemented.

Key words: process optimization; machine learning; metaheuristic methods; sustainable projects; effective management

1. INTRODUCTION

Sustainable measures must be taken into account at all stages of the investment process: starting from planning, design, construction, and operation. This approach is required not only by regulations, but also by investors, contractors and even residents. Scientific publications on optimization show that the use of combinatorial optimization models and algorithms can effectively solve practical problems in construction [1]. Modeling of construction processes is often carried out using discrete optimization models, which effectively capture nonlinear dependencies and the uniqueness of objects, while meeting technological and quality requirements of construction processes [2].

An example of digital transformation is the optimization of the duration of work activities when erecting structures. The result can be a reduction in the duration of works, an increase in the productivity of workers, minimizing the risk of delays and disruptions. As a result, productivity can be maximized, and the risk of increased costs associated with site maintenance, among other things, decreases. This reflects the concept of sustainable execution of works, which can be enhanced through the use of metaheuristic methods and artificial intelligence, both at the planning stage and during the project's operation. Sustainable urban construction, also includes aspects such as the use of energy-efficient technologies that, even during construction, can significantly reduce greenhouse gas emissions and resource consumption. Incorporating such solutions into urban projects supports the green transformation of cities.

Solutions are anticipated in the domain of optimizing productivity and efficiency in work processes to achieve optimal outcomes. Under-performance of blue-collar workers, among others, is associated with increased construction time and can simultaneously disrupt other processes. Consequently, creating performance management systems that can assess (with satisfactory probability) the estimated productivity of a worker under specific conditions for specific construction work is crucial. The system should also take into account soft techniques. In the present study, a system based on a metaheuristic approach is proposed, and artificial intelligence models augmented with a proprietary algorithm have been developed.

In [3], the authors propose an innovative approach to optimize construction management using metaheuristic methods and Bayesian networks. The algorithmic steps of metaheuristic optimization of the construction process were developed. The optimization procedures used for the research were based on the rules of the golden ratio [0.38; 0.62]. The effectiveness of the proposed scientific ideas was confirmed through the means of

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optimization modeling of Bayesian networks (see also [4]). The work revealed the scientific potential of applying metaheuristics in construction optimization processes not only in production management, but also in predicting future problems. The present article is a continuation (expansion) of research related to metaheuristic optimization of construction. The relationship with previous scientific approaches to optimization by metaheuristic methods is revealed, the detailing of the harmony search algorithm is supplemented, and an innovative modification of network management is proposed, which increases the reliability of data and increases the efficiency of optimization as a whole [5].

Also, it is worth noting that the developer is constantly trying to make the construction project better and draws on a variety of practices and experience to do so [6, 7]. It is proposed that the optimal management decision reflects the characteristics and functions of the forward-looking thinking of a civil engineer. The success of effective decision-making ensures the reliability of the initial data of a construction project [8].

It is known that the main functions of foresight are reasoning and balancing. Reasoning refers to actions related to structures, namely synthesis (construction) and analysis (decomposition). Balancing means finding an optimal solution between two extreme cases [9].

To implement predictive modeling, one can develop a thinking model (or calculation model) that incorporates memory and time. The forward-thinking model is based on three aspects: reasoning, balancing, and the nature of memory/time. These aspects describe the essence of optimization programming using metaheuristics. To understand what any optimal strategy looks like, we need to consider the principle of the balancing apparatus. It is known that balancing is one of the most important cognitive functions involved in making management decisions in construction. Optimization by the harmonic component is the search for a balanced solution between two extreme variables [*best* ... *worst*]. The mathematical form of balancing is well represented by the golden ratio shown in Eq. (1).

$$1 = \frac{a \cdot b}{(a+b) \cdot (a-b)} \tag{1}$$

The solution to this equation is a variable with a golden ratio value of ≈ 0.618.

Adapting this equation to describe abstract structures, which are models of construction projects, will be a mathematically transformed expression of balancing the golden ratio, which contains the complexity function f^{comp} , the similarity function f^{sim} and the difference function f^{dif}. All the proposed functions form a harmonic equation for balancing the elements of the production management system. The harmonic value regulates the balance between similarity and difference shown in Eq. (2).

$$\frac{f^{comp}(a) \cdot f^{comp}(b)}{f^{comp}[f^{sim}(a;b)] \cdot f^{comp}[f^{dif}(a;b)]} = H(a;b) = 1 \tag{2}$$

This approach confirms the need to balance the mutual complexity of objects through their similarities and differences.

This research paper aims to implement this approach using metaheuristics methods, namely by harmonic optimization, i.e., by applying the harmony search algorithm.

All tasks of construction production planning are focused on finding a state of the object that will meet a certain optimality criterion with efficient resource allocation. In this research, the development and study of metaheuristic algorithms for solving practical problems of optimizing construction production.

Metaheuristics are knows as a powerful and extremely popular class of optimization methods that allow us to find solutions for a wide range of problems from various fields of activity, including very effective in construction production planning. The advantage of metaheuristic methods is that they make it possible to solve intractable optimization problems and operate on strategies that guide the search for solutions. Metaheuristic algorithms use a direct random search for possible solutions (optimal or close to optimal) to a scientific problem until the final criterion (the limit of the maximum number of iterations) is reached. The priority of metaheuristics is to effectively explore the search space to identify optimal (near-optimal) solutions [10].

Despite the fact that construction optimization tasks have their own individual characteristics of behavior when solving various scientific problems, all metaheuristic algorithms have a number of common components and function within a certain number of categories:

1. initialization – definition and ways to find the initial solution,
2. functioning space – each solution corresponds to a set of functioning spaces and the links between them,
3. segregation of the functioning space is based on the choice condition and behavioral features,
4. determination and evaluation of components for the implementation of the optimization process, taking into account the set of transitions between iterations,
5. acceptance of the result – determining the best result and giving it the status of the optimal result,
6. stopping criterion – stopping the algorithm based on the accepted stopping criterion.

2. SCIENTIFIC MATERIALS AND METHODOLOGICAL BASE

2.1. Justification of the Research Field

Traditional design and construction of building foundations requires a focus on the continuous improvement of construction processes. There is no doubt that conservative approaches to foundation construction have many years of experience in widespread application in production around the world. However, in the context of the rapid development of civilization and the growth of anthropogenic requirements of mankind, ineffective results arise. Such circumstances require improvement of existing production methods.

This research article presents an approach of applying the harmony search method metaheuristic optimization algorithm, which can be used to improve foundation construction. The harmony search method has been applied in the construction of manually executed earthworks. In this research, the metaheuristic algorithm is modified to take into account the peculiarities of the processes of organizing and managing construction production. The process of harmony search in creating harmonious music that is both pleasing and appealing to the ear is similar to the search for optimality in the process of optimizing various directions. The harmony search algorithm (HSA) is known in science as one of the most powerful metaheuristic optimization methods inspired by musicians' ability to improvise, which involves less mathematical effort and highly accurate results. The harmony search method mimics the creative process of a performing musician. The main idea of the harmony search method is to model the process of harmony selection by a performing musician, i.e. to create pleasant music.

In the process of implementing the method, when creating music, the musician selects the right note to achieve the best harmony. Each decision of the musician, which is selected from the set of valid decisions, generates a corresponding value of the objective function in order to achieve a global extremum. All notes that fall out of the general harmony range are replaced by more aesthetically pleasing ones.

The choice of a particular pitch can be made in the following ways according to several alternatives:

- option 1 – the musician recalls a successful sound combination and plays the corresponding note,
- option 2 – the musician plays the note next to the one that is stored in his or her memory,
- option 3 – the musician plays a random note from all possible notes.

This process of harmonic search is formalized by the creators of the method in the form of an algorithm, where the pitch (note) corresponds to the value of a variable, the sound combination is a solution from the set of possible solutions, and the effect of the harmony sound is the value of the objective function that corresponds to the selected values of the variables.

2.2. Implementation of Harmony Search Algorithm

A certain number of solutions are generated on the set of valid solutions (the space of all solutions in the world around us). For each solution (for each sound combination), the value of the objective function is calculated. All the coordinates of the solution (sound combination), along with the corresponding function value, are placed in a matrix referred to as Eq. (3), known as the harmony memory (HM). Among all the solutions (sound combinations) stored in the memory, the worst one is identified as the candidate for replacement. Next, a new solution (new sound combination) is generated and compared to the worst one in HM. If it turns out that it is better in terms of the objective function, then this solution is placed in the harmony memory instead of the worst one. After the described substitution in the harmony memory (i.e., after "improving" the worst option), the worst solution is found for the next comparison. The search process ends when the maximum number of iterations is reached [11, 12].

The coordinates of the new solution are generated independently of each other. To obtain the value of the next coordinate x_j^i, the corresponding coordinate of the solution is chosen with a certain probability, which is randomly selected from the harmony memory. Otherwise, a random value is selected in the interval, which determines the permissible values of this coordinate.

If the value of a decision variable is taken from the harmonic memory, then with a given probability it is corrected by a small increment (addition or subtraction). If no correction is performed, the uncorrected value of the coordinate is used.

The components of the harmony search algorithm are compared with the variables of management optimization in construction. A single musical note x_j^i is a variable in the management decision vector, a sound combination (individual harmony) H is equated with the management decision vector, the melody and the resulting effect from its sound f are the objective function of the decision vector, the harmony memory (HM) reflects the knowledge and experience of the person making the management decision.

The sequence of algorithmic stages consists of the following steps:

- Step 1. Initialization of the algorithm. Introduction of the optimization program and parameters for the algorithm.
- Step 2. Initialization of the solution set.
- Step 3. Generating a new solution vector, improvising a new harmony.
- Step 4. Harmony memory updating.
- Step 5. Evaluation of the termination rule (stopping criterion).
- Step 6. Final results of the algorithm.

In the harmony search algorithm (HSA), each possible control decision is called a "harmony", and each decision variable corresponds to a musical note. Harmony memory (HM) is a memory area where all decision vectors (sets of decision variables) are stored.

For this scientific study (to optimize any construction process), it is possible to enter any number of solutions to form a harmony memory.

The harmony memory is filled with randomly generated solutions (decision vectors). The scientific hypothesis of this article involves the concept of filling the harmony memory based on the professional knowledge, skills and production experience of the developer (managerial decision maker) [13, 14].

The values are stored according to the objective function, and a harmonic memory matrix (HM) is formed. A mathematical representation of the harmonic memory is provided in Eq. (3):

$$\mathrm{HM}=\left\{\begin{array}{ccccc|c} x_1^1 & x_2^1 & x_3^1 \cdots & x_n^1 & f(x^1) \\ x_1^2 & x_2^2 & x_3^2 \cdots & x_n^2 & f(x^2) \\ \vdots & \vdots & \vdots \cdots & \vdots & \vdots \\ \vdots & \vdots & \vdots \cdots & \vdots & \vdots \\ x_1^{hms} & x_2^{hms} & x_3^{hms} \cdots & x_n^{hms} & f(x^{hms}) \end{array}\right\}=\left\{\begin{array}{c} H_1 \\ H_2 \\ \vdots \\ \vdots \\ H_N \end{array}\right\} \quad (3)$$

where:

hms – is the harmony memory size is the number of solution vectors in the harmony memory.

At the end of the algorithm, the best harmony stored in the harmony memory (HM) is set as the optimal solution to the scientific problem under study.

Among the newly generated solutions x_{new} stored in the harmony memory, the one with the best value of the objective function $f_{new}(H_{NEW})$, as defined in Eq. (4), is identified.

$$x_{new} = x_{best} \rightarrow H_{new} = H_{best} = H_{opt} \qquad (4)$$

The basic methodology of the harmony search algorithm confirms its potential for its use in optimizing construction in the context of balanced development.

2.3. Modification of the harmony search algorithm using the system management model

This study introduces an innovative modification to the harmony search algorithm (HSA) by proposing the application of a specialized methodology during the initialization phase. The approach involves constructing the initial harmony memory based on principles of system control and systemology, ensuring a structured and theoretically grounded foundation for the optimization process.

The essence of this methodology is to represent the initial harmony memory of the algorithm in the form of a functional system of external and internal construction factors. The authors propose to use a special model of systematic management, which is based on the general principles of systemology. This methodology of the systematic approach ensures the fastest possible achievement of the ultimate functional goal. It involves creating an interdependent, purposeful set of memory system elements. These elements work together to achieve a predefined useful result, specifically the harmonization of the production system. The main system-forming factor recognizes this harmonization at the initialization stage of the harmony search algorithm.

In this scientific study, the harmony memory is a complex system consisting of interconnected elements and interrelationships between them. In the context of harmonization of system management and the use of promising strategies, the methodology of technological reliability of the production system is also used [15].

The reliability of a production system is a complex property of the production system to function at a satisfactory level within a given time period, with the acquisition of quantitative time characteristics, such as reliability, functionality, reliability, durability, stability, survivability, safety, etc.

Determination of technological reliability in the assessment of the result implies, if necessary, structural reorganization of the system and functional replacement of some elements (unreliable, failed) with other elements that previously performed other functions to ensure a given result.

This approach requires the developer (or decision maker) to adhere to a well-defined structural framework for harmony memory, incorporating key principles of systems engineering—such as a specified composition of elements, interconnections, and empirical data. The realization of the research innovation is reflected through the list of complete control functions, system behavior of elements and transformations between information modules of the system in the process of optimization [16].

The aim is to determine the reliability of the initial harmony memory (HM) at the initialization stage of the algorithm (HSA) using the principles of system control. The indicator of the technological reliability of the system of elements of the initial harmony memory (HM) at the initialization stage will reduce the number of algorithmic iterations and speed up the optimal decision-making in construction.

The authors of the study propose that the reliability of the algorithm initialization stage is based on the system-forming factors of the construction environment (atmospheric phenomena, working conditions, biological factors, functional barriers) and the professional responsibility of the developer (professional knowledge, specialized standards, professional skills, professional experience, professional competencies, innovation, self-control, endurance).

The system-forming factors are united by certain functions into three main groups: information modules of management, actions of the management subject, and management tasks.

The group of factors of the information module of management contains indicators of the information state of a separate variable of the decision vector x_j^i. The information state changes the measure (par) of a separate variable of the decision vector (a separate element of the harmony memory system), which leads to a new material content of this element.

To introduce seven information modules into the model of systematic control of algorithm initialization (HSA):

1. Assessment of the state of management of the object (Ψ_1);
2. Determination of the subject's own state of management (Ψ_2);
3. Determination of the state of neighboring objects with which interaction is performed (Ψ_3);
4. The state of the environment in which the system elements interact (Ψ_4);
5. The state of the structure that carries out management (management entity) (Ψ_5);
6. Instructions and restrictions from higher management structures (Ψ_6);
7. Distinction-methodology (awareness of the system management process through the combination of all seven information modules) (Ψ_7).

Management functions ensure the circulation of information and information transformation in the management process and also reflect the sequence of actions of the management entity:

1. Recognition of the environment factor, i.e. the factor that affects the system with which the intelligence is faced (X_1);
2. Formation of a recognition stereotype, i.e. recognition of the environment factor for the future (X_2);
3. Forming a vector of goals for each environmental factor and adding the time vector to the overall vector (X_3);
4. Formation of the target function (concept), management based on the solution of the problem of sustainability by foresight (X_4);
5. The organization of a management structure that manages and carries the target management function (X_5);

6. Control, monitoring of the system structure in the process of management (X_6);
7. Maintaining performance or liquidation - maintaining the performance of the structure in the management process or its liquidation (if necessary) (X_7).

Full management functions can be realized only in an intelligent management scheme, which implies the creativity of the management system, the presence of the manager's intelligence, who is obliged to solve the following tasks:
1. Identification of environmental factors that affect the production system (this cannot be done without a creative approach) (χ_1);
2. Formation of goal vectors (this is also a creative process) (χ_2);
3. Formation of new management concepts (how to do all this, what new tools to use, what promising forces?) (χ_3);
4. Improvement of the methodology of forecasting and correction in solving sustainability problems by predictability according to the "predictor-corrector" scheme (χ_4);
5. The ability of the control system to independently produce a new information module based on the control systemology (χ_5).

To enhance the reliability of the HSA algorithm's initialization, a system-forming model should be employed—one that accurately reflects the structure and logic of complex interactions among the elements within the harmony memory.

The model in Fig. 1 reflects the interconnection of information modules, complete functions of production system management and combines the states of the system's perspective development through the following transformation phases: the first phase is the phase of system environmental conditions (initial data); the second phase is the phase of information capabilities of functional flows; the third phase is the phase of an intelligent control scheme; the fourth phase is the phase of implementation of functional processes of system management; the fifth phase is the phase of system state formation; the sixth phase is the phase of targeted possibilities.

3. RESULTS

3.1. Experience and preliminary research

The application of a modification of the metaheuristic harmony search algorithm (HSA) was realized on the example of manual excavation of soil for a foundation. Using empirical data enriched by artificial intelligence, a systematic method is applied to control the reliable formation of the initial harmony memory (HM) at the algorithm initialization (HSA) stage. The system-forming model uses a systematic and logical approach to arranging components.

The design and project management subsystems are responsible for making technical decisions that must account for the requirements of all construction-related subsystems, while simultaneously optimizing key performance criteria such as cost, time, and resource utilization. The values of these optimality criteria serve as indicators of overall project performance and provide a basis for making well-balanced, effective decisions in construction management.

Based on the concept of systematic construction management, the authors of this study propose to carry out combinatorial optimization of the empirical data of the experiment to increase its systemic reliability. The external and internal environmental factors that form the initial conditions for the functioning of the production system are the initial components of the initial harmony memory at the stage of initialization of the harmony search algorithm. The initial elements of the initial memory of harmony, being part of the system-forming control model, begin the modified process of the harmony search algorithm (HSA). The intellectual interaction of information management modules (ψ), strategies of the management entity (X) and management tasks (χ) implements the work of the systemological management model.

The systematic control innovation performs combinatorial optimization of the initial data in neural systems by organizing, transforming, combining, adjusting, evaluating, and checking the coincidence of elements.

The next step is to control the functioning of the production system. After that, the systemic reliability of the system is

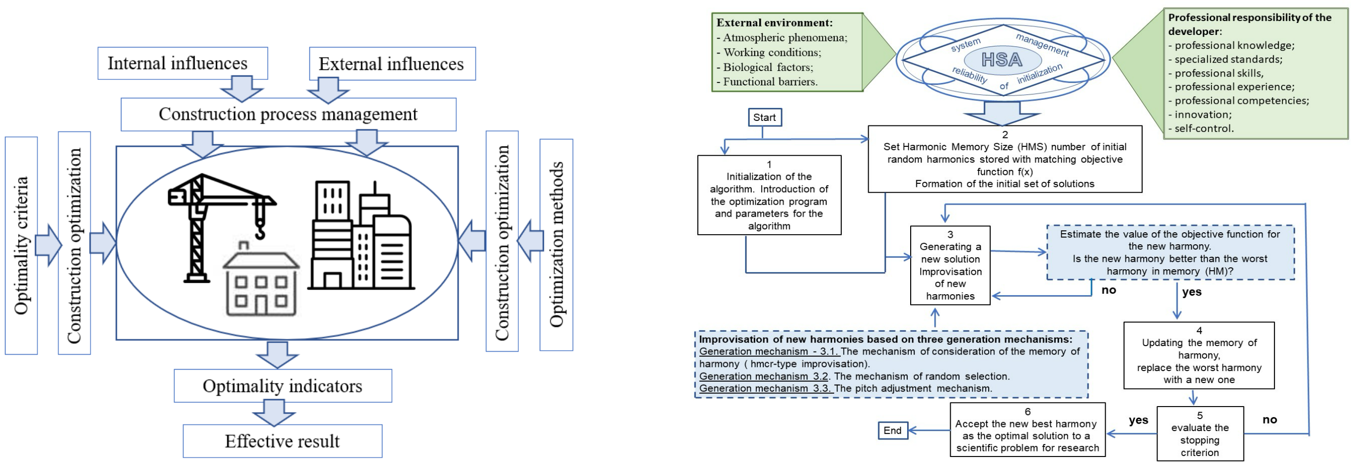

Fig.1. Implementation of optimization methods in construction (left) and modification of the harmony search algorithm using the system management model (right) (source own findings based on [11, 12])

determined. The result of this process expands the space of successful management decisions of the management entity, increases their systemic reliability, i.e. gives additional confidence and determination to the decision maker.

After that, influential system reliability flows are formed, which are aimed at determining special system reliability coefficients (*R*) for each memory element, according to the production type of the individual component (time, labor intensity, productivity, cost-effectiveness, cooperation, etc.). The system reliability coefficients allow to increase the reliability of the initial literacy memory at the stage of algorithm initialization.

The initial variables, which are formed on the basis of empirical data from a scientific experiment, are modified by the system reliability coefficients x_R. After that, the modified variables form a modified harmony memory, which is improved by introducing system reliability into it Eq. (5):

$$\mathrm{HM}^{R*} = \begin{Bmatrix} x_{R1}^{1} & x_{R2}^{1} & x_{R3}^{1} \cdots & x_{Rn}^{1} \\ x_{R1}^{2} & x_{R2}^{2} & x_{R3}^{2} \cdots & x_{Rn}^{2} \\ \vdots & \vdots & \vdots \;\cdots & \vdots \\ \vdots & \vdots & \vdots \;\cdots & \vdots \\ x_{R1}^{hms} & x_{R2}^{hms} & x_{R3}^{hms} \cdots & x_{Rn}^{hms} \end{Bmatrix} \tag{5}$$

Further work of the harmony search algorithm does not change and is shown in Fig. 2.

Using this innovative method of modifying the algorithm, a decision-making engineer in construction receives special indicators of system reliability - system reliability coefficients (*R*). With the help of the principles of system control and system reliability coefficients, the input elements of the harmony memory (HM) are adjusted, so that each element (variable) of the management decision vector x_{newRj}^{i} increases the level of reliability, and the decision vector $H_1 = x_1^1, x_2^1, \dots, x_j^i, \dots, x_n^{hms}$ itself acquires the level of optimality. In general, such a modification improves the performance of the harmony search algorithm, reduces the number of algorithmic iterations, and speeds up the optimal decision-making in construction.

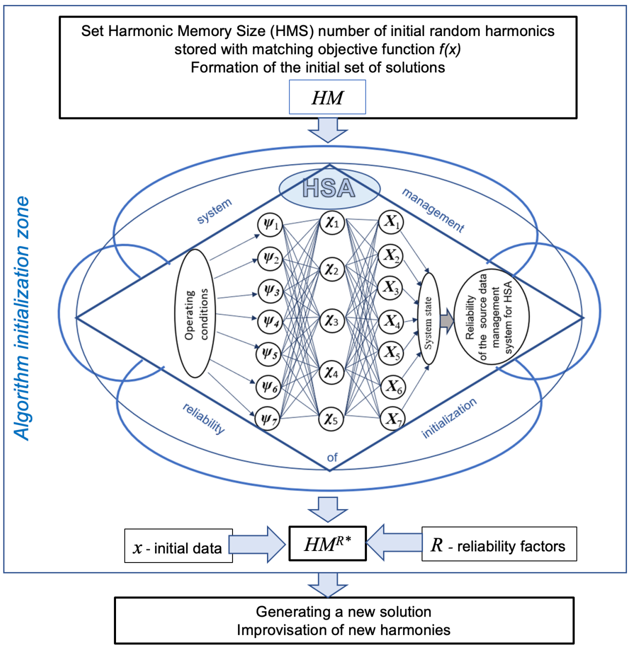

Fig.2. Detailed visualization of the systematic modification of the harmony search algorithm (HSA) (source own)

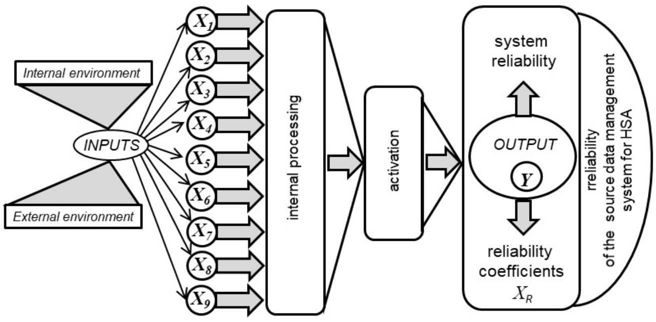

Fig.3. Scheme of the created networks and machines (source own based on [17, 19])

This article presents an analysis of the impact of various environmental factors and worker characteristics on the efficiency and quality of work performed. The time frame considered the spring and summer period, taking into account atmospheric conditions, ground data and worker information. Measurements and data collection were carried out in construction projects of low-rise residential buildings during the construction of reinforced concrete strip foundations.

Atmospheric conditions included the value of air temperature, humidity and precipitation. Inputs were developed based on the knowledge of experts and practitioners. Based on expert knowledge, relationships between atmospheric factors such as air temperature, humidity and precipitation were established and included in the analysis. Soil data includes soil classification based on geotechnical documentation for various construction sites, taking into account the type of soil and other physical and chemical properties that could affect the difficulty of the earthwork. Information on workers included their work experience, assessed by the number of years they have worked in the construction industry, physical capabilities, and the effectiveness of teamwork, as observed by experts over the years. The algorithm binding the mentioned parameters was based on artificial intelligence and machine learning. Artificial Neural Network model and Support Vector Machine have been used.

Artificial Neural Networks (ANNs) [17, 18] and Support Vector Machines (SVMs) [19] have been created, with independent parameters assumed: Temperature, Humidity, Soil category, Rain factor, Group cooperation coefficient, Experience years, Physical endurance and Time of day indicator. For the ANNs, the samples have been divided into subsets: 70% learning, 15% testing and 15% validation. And in the case of SVMs, 75% learning sample and 25% testing.

TABLE 1. Selected 4 created artificial neural networks with the best parameters

Network no.	Quality (general) [%]	Quality (learning) [%]	Quality (testing) [%]	Quality (validation) [%]
1	90.48	85.71	92.86	92.86
2	88.10	85.71	92.86	85.71
3	83.33	85.71	78.57	85.71
4	80.48	70.00	92.86	78.57

Figure 3 shows the scheme that has been used to create networks and machines. Table 1 presents the results from the created neural network models, which have been created by adopting different error, internal processing and activation functions. The 4 networks with the best adaptations are selected. Model general accuracy was even 90.48 %.
Support vector machines have been created with different parameters. Due to the fact that the research problem is linearly unseparated, a transformation has been performed using different kernel functions. The 4 machines with the best results were selected, which are shown in Table 2.

TABLE 2. Selected 4 created support vector machines with the best parameters

Machine no.	Quality (general) [%]	Quality (learning) [%]	Quality (testing) [%]
1	89.15	86.30	92.00
2	88.47	84.93	92.00
3	88.47	84.93	92.00
4	85.83	87.67	84.00

The learning machine has given good results as the networks. Classification accuracy was even 89.15 % for all samples.
A sensitivity analysis of the data showed that all the parameters adopted had a significant impact on the pace of work. High temperatures and low humidity led to faster fatigue of workers, which reduced their productivity. Precipitation in the last days before the start of the work affected the moisture content of the soil, which made manual excavation more difficult. The type of soil determined the difficulty of the work, with clay soils being more demanding to work on than sandy soils. Workers' experience had a direct impact on the quality and speed of the work, with more experienced workers performing better in difficult conditions. Team cooperation was a key factor in work efficiency, and teams that worked better together achieved better results.
This research confirms that both environmental factors and worker characteristics have a significant impact on the efficiency of manual excavation. Further research is recommended in the future to develop optimal strategies for working under different conditions.

4. DISCUSSION AND CONCLUSIONS

The results of this study highlight the potential of the harmony search algorithm in enhancing construction management processes through metaheuristic optimization. The initial modification of the algorithm demonstrates a promising step towards a more comprehensive scientific framework. This approach not only addresses the immediate challenges in construction management but also sets the stage for future advancements in the field.
It is important to emphasize the advantages of the present algorithm over the classical approach. Unlike classical optimization methods, metaheuristic methods can be used in situations where we have virtually no information about the nature and properties of the function under study. Heuristic methods based on an intuitive approach make it possible to find good enough solutions to the problem without having to prove the correctness of the procedures used and the optimality of the result obtained. In this case, computational costs are considered an important factor. Metaheuristic methods combine one or more heuristic methods (procedures) based on a higher-level search strategy. They are able to go beyond local extremes and perform a fairly complete exploration of the set of possible solutions. Metaheuristic optimization manages the efficiency of a design to find both optimal and suboptimal (satisfactory) results. Metaheuristics balances competing optimality criteria in managing fuzzy logic systems, which are construction management systems.
One of the key findings is the algorithm's ability to handle the complexity of coordinating heterogeneous optimization criteria. A key finding is the algorithm’s demonstrated capacity to effectively manage the complexity associated with coordinating heterogeneous optimization criteria. This is particularly significant in the construction industry, where the integration of various technical and organizational factors is crucial for effective project management. The harmony search algorithm's adaptability to these multifaceted requirements underscores its potential as a robust tool for optimizing construction workflows.
The study also underscores the importance of geophysical data in the foundation phase of construction. By incorporating critical geophysical parameters into the algorithm, the research ensures that the foundation works are planned and executed with a high degree of precision. This integration not only enhances the stability and safety of the structures but also optimizes the use of resources, thereby reducing costs and improving efficiency.
Furthermore, the development of an automated control algorithm based on metaheuristics represents a significant innovation in the field. This algorithm extends the application of digital information technologies across various stages of construction projects, from design and modeling to implementation and quality management. By drawing inspiration from biological systems, the research introduces a novel perspective on construction management, emphasizing the importance of adaptive and intelligent systems.
The practical implications of this research are manifold. The creation of an intelligent metaheuristic optimization software algorithm for manufacturing process simulation provides a valuable tool for construction managers. This tool can facilitate better decision-making, streamline production workflows, and enhance overall productivity. Moreover, the algorithm's guidelines for planning and executing foundation works offer a practical framework for addressing the most critical aspects of construction projects.
The article under consideration continues the scientific direction of the authors' research using strategies of metaheuristic algorithms (the golden section method and the Bayesian method) to optimize various production processes in construction. This study covers the development of foundation construction innovations and digital transformation using a harmonic search algorithm that successfully uses the concept of memory (experience and competence of the builder) to make

optimal design and engineering decisions. The paper shows the effectiveness of applying the harmony search algorithm in engineering problems of construction, taking into account the technological features of construction processes, which are an example of stochastic systems.

The result of the scientific work is an innovative way to modify the harmony search algorithm (HSA) using the model of system management and systemology. The beneficial effect of this innovation will ensure the reliability of the initial data that form the harmony memory at the initialization stage of the HSA algorithm, which speeds up the process of optimizing a construction project. With the help of metaheuristic strategies, it is possible to overcome the complexity of making optimal engineering and technical decisions and increase the use of innovations in construction. The presented scientific development opens up promising possibilities for the application of information technologies in construction management, taking into account the instability of environmental factors. Metaheuristic optimization performs multiple checks of the production model of the project at the level of simple operations and is easily implemented by mathematical programming tools using a digital environment (Android, Windows). This approach increases the reliability of management decision-making for the developer, being in a zone of trusting comfort. Ultimately, the algorithm is expected to have the ability to develop heterogeneous optimization criteria, which is extremely important in engineering practice, where the diversity of data and requirements often makes it difficult to model decision-making systems.

The initial success of the harmony search algorithm in this context indicates that its further development and refinement may yield substantial advancements in the field. This innovative solution increases the accuracy of foundation work planning and allows for real reductions in construction costs and risks. A valuable element of the study is also the reference to real implementation aspects through the development of intelligent simulation software to support construction management, which can have direct application in the professional practice of project managers and contract engineers. The main limitation so far has been the database, which must be expanded in the future for validation purposes. An important test of quality will be the pilot implementation of the system in practice. Future research should aim to enhance the algorithm's capabilities, extend its application to additional phases of the construction process, and integrate it with emerging technologies to support a holistic and intelligent approach to construction management.

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REFERENCES

[1] I. Arutiunian, M. Poltavets, M. Achacha, O. Bondar, F. Pavlov, O. Gerasymenko, and T. Kulinich, “Effective Concepts of Harmonious Management of Production Systems,” *Int. J. Comput. Sci. Netw. Secur.*, vol. 21, pp. 141–144, 2021, doi: 10.22937/ijcsns.2021.21.3.19.

[2] I. Arutiunian, M. Poltavets, O. Bondar, V. Anin, and F. Pavlov, “Structural Information Management of Production Systems in Construction,” *Int. J. Adv. Trends Comput. Sci. Eng.*, vol. 9, pp. 4794–4797, 2020, doi: 10.30534/ijatcse/2020/87942020.

[3] A. Jakubczyk-Gałczyńska, A. Siemaszko, and M. Poltavets, “Optimizing Construction Engineering Management Using Metaheuristic Methods and Bayesian Networks,” *Applied Sciences*, vol. 14, no. 11, p. 4871, 2024, doi: 10.3390/app14114871.

[4] A. Siemaszko, A. Jakubczyk-Gałczyńska, and R. Jankowski, “The Idea of Using Bayesian Networks in Forecasting Impact of Traffic-Induced Vibrations Transmitted through the Ground on Residential Buildings,” *Geosciences*, vol. 9, p. 339, 2019, doi: 10.3390/geosciences9080339.

[5] M. Çevikbaş and Z. Işık, “An Overarching Review on Delay Analyses in Construction Projects,” *Buildings*, vol. 11, p. 109, 2021, doi: 10.3390/buildings11030109.

[6] A.M. Faten Albtoush, “Risk of Delay in Construction Projects,” in *Risk Management in Construction—Recent Advances*, London, UK: IntechOpen, 2024, doi: 10.5772/intechopen.112594.

[7] T. Goetz, The Decision Tree: *How to Make Better Choices and Take Control of Your Health*, Emmaus, PA, USA: Rodale, 2010, ISBN: 1605291684.

[8] Y. Panova and P. Hilletofth, “Managing supply chain risks and delays in construction project,” *Ind. Manag. Data Syst.*, vol. 118, pp. 1413–1431, 2018, doi: 10.1108/IMDS-09-2017-0422.

[9] T. Akintunde and D. Morel, “Analysing the Impact of Risk Management Practice on Construction Project Performance: A Systematic Literature Review,” *SSRN*, 2023, doi: 10.2139/ssrn.4585886.

[10] F.E. Gill, W. Murrey, and M.A. Wright, *Practical Optimization*, Cambridge, MA, USA: Academic Press; Stanford, CA, USA: Systems Optimization Laboratory, Department of Operation Research, Stanford University, p. 402, 1981, doi: 10.1137/1.9781611975604.

[11] A. Askarzadeh and E. Rashedi, “Harmony Search Algorithm: Basic Concepts and Engineering Applications,” in *Recent Developments in Intelligent Nature-Inspired Computing*, Chapter 1, 2017, 36 p., doi: 10.4018/978-1-5225-2322-2.ch001.

[12] Z.W. Geem, *Music-Inspired Harmony Search Algorithm. Theory and Applications*, Springer, 2009, 216 p., doi: 10.1007/978-3-642-00185-7.

[13] A.E. Ezugwu, A.K. Shukla, R. Nath, A.A. Akinyelu, J.O. Agushaka, H. Chiroma, and P.K. Muhuri, “Metaheuristics: A comprehensive overview and classification along with bibliometric analysis,” *Artif. Intell. Rev.*, vol. 54, pp. 4237–4316, 2021, doi: 10.1007/s10462-020-09952-0.

[14] D. Greiner, J. Periaux, D. Quagliarella, J. Magalhaes-Mendes, and B. Galván, “Evolutionary algorithms and metaheuristics: Applications in engineering design and optimization,” *Math. Probl. Eng.*, 2018, doi: 10.1155/2018/2793762.

[15] M. Abd Elaziz, A. Dahou, L. Abualigah, L. Yu, M. Alshinwan, A.M. Khasawneh, and S. Lu, “Advanced metaheuristic optimization techniques in applications of deep neural networks: A review,” *Neural. Comput. Appl.*, vol. 33, pp. 14079–14099, 2021, doi: 10.1007/s00521-021-05960-5.

[16] S. Chattopadhyay, A. Marik, and R. Pramanik, “A Brief Overview of Physics-inspired Metaheuristic Optimization Techniques,” *arXiv*, arXiv:2201.12810, 2022, doi: 10.48550/arXiv.2201.12810.

[17] K. Kuźniar and Z. Waszczyszyn, “Neural simulation of dynamic response of prefabricated buildings subjected to paraseismic excitations,” *Comput. Struct.*, vol. 81, pp. 2353–2360, 2003, doi: 10.1016/S0045-7949(03)00310-9.

[18] K. Kuźniar, “Neural networks for the analysis of mine-induced building vibrations,” *Computer Assisted Mechanics and Engineering Sciences*, vol. 18, pp. 147–159, 2011. [Online]. Available: https://cames.ippt.pan.pl/index.php/cames/article/view/111/102

[19] S. Haykin, Neural Networks and Machine Learning, Upper Saddle River, NJ, USA: Pearson, Prentice Hall, 2009. [Online]. Available: https://dai.fmph.uniba.sk/courses/NN/haykin.neural-networks.3ed.2009.pdf

[20] H. Alimoradi and M. Shams, “Optimization of subcooled flow boiling in a vertical pipe by using artificial neural network and multi objective genetic algorithm,” *Appl. Therm. Eng.*, vol. 111, pp. 1039–1051, 2017, doi: 10.1016/j.applthermaleng.2016.09.114.