ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

UDC 519.86: 658.5: 621.31

doi: 10.32620/reks.2024.3.13

Mykhailo BUHAIEVSKYI, Yuri PETRENKO

Kharkiv National Automobile and Highway University, Kharkiv, Ukraine

SIMULATION OF PRODUCTION AND LOGISTICS FOR CONCRETE PLANTS

The focus of the current research *is the multi-criteria task of decision-making support for the effective management of ready-mix concrete production and its delivery to construction sites, taking all possible risk factors into account. The development of a simulation model for the network of production facilities and the distribution chain of ready-made concrete mixtures is a key element of the project to create a digital twin in the production and logistics of a concrete plant.* ***The relevance*** *of this study is supported by the fact that post-war restoration of the destroyed housing stock, reconstruction of damaged infrastructure and industrial buildings, and the resumption of work at all construction sites in the country will lead to a sharp increase in the demand for concrete, which will obviously exceed the existing production capacity. Therefore, one of the top priorities for Ukrainian concrete plants today should be the implementation of a strategy and relevant development projects aimed at increasing productivity without losing quality.* ***This research aims*** *to create a simulation model of the production and delivery of ready-mixed concrete in a network of manufacturing plants and construction sites, as part of a project to create a digital double for making effective risk management decisions in real-time for the early detection of suboptimal activity in the production of high-quality concrete mix and its effective logistics. Thus,* ***the objectives*** *of the study are as follows: to analyze the problems and features of creating digital duplicates in the production and logistics of concrete plants; to develop a simulation model of analyzing production processes and logistics of ready-mixed concrete mixtures; to provide an illustrated example of modeling production and logistics processes in a network of concrete factories and construction sites; to conduct optimization experiments to determine the modes of system operation. After all necessary work had been done, the following* ***results*** *have been obtained. A simulation model of the analyzing production processes and logistics of ready-mixed concrete mixtures has been developed, with the help of which it is possible to solve several tasks, including the evaluation of the rationality and efficiency in the organization of production and delivery of ready-mixed concrete, the identification of bottlenecks in production and logistics processes, forecasting of indicators activities of concrete plants, taking into account changes in production conditions, and forming data for decision-making on reducing plant and customer downtime, among others.* ***Conclusions****. The academic novelty of the study is related to the solution of the actual problem related to the preparation and planning of logistical actions for the delivery of ready-mixed concrete in the network of plants and construction sites by-creating a complex of optimization and simulation models, that contributes to the effectiveness of decision-making on risk management for the early detection of suboptimal activities in the production of commercial concrete mixtures and logistics. The effectiveness of the proposed approach is illustrated by an example of concrete delivery in a network of concrete factories in the Kharkiv region.*

Keywords: *ready-mixed concrete; concrete delivery; supply chain; simulation modeling; agent modeling; transportation.*

1. Introduction

Suppliers of ready-mixed concrete mixtures belong to the group of most important participants in construction projects, and logistics represent significant challenges in the ready-mixed concrete industry [1]. Restoration of destroyed residential areas, reconstruction of damaged infrastructure and industrial buildings, and resumption of activities at all construction sites in the country will lead to a sharp increase in demand for concrete, which will obviously exceed existing production capacities. Therefore, one of the top priorities of Ukrainian concrete plants today should be the implementation of a strategy and relevant development projects aimed at increasing productivity without loss of quality. Currently, the biggest drivers of demand for concrete are infrastructural construction, the construction of fortifications, and various military defense structures, as well as reconstruction works in war-torn regions.

Critical risks in the production and logistics of ready-mixed concrete [2, 3] may be associated with the following factors: inefficient planning in the operation of the concrete-mixing equipment and the delivery itself; queues or loading errors; long downtimes waiting for pouring at construction sites; inconsistency of actions with the client; delays in transport for loading or unloading; suboptimal delivery routes; deviation from the route during delivery, etc. All these issues, in the long run, lead to difficulty in finding the optimal balance of supply and transport costs, violation of production plans, and incomplete use of plant capacities. The answer in the asphalt and concrete industry and in the logistics of bulk materials to solve these problems and manage their production operations with a greater response to risks is the transition to the use of Industry 5.0 technologies—digital twins, industrial Internet of Things, and digital modeling [4, 5].

Combining the virtual and physical worlds with Digital Twins technology enables ready-mix concrete producers to avoid problems before they occur, reduce operational disruptions at customer sites, prevent downtime and effectively plan activities and delivery schedules through simulation [6].

The key elements of the digital double (twin) are an industrial automation system based on the Internet of Things for obtaining technological data in real-time, a dynamic simulation model of a digital double in the production and logistics chain, and advanced predictive analytics for making predictive decisions regarding production, logistics, and maintenance [7]. With the model and data, we can build powerful digital twin software for experimentation, analysis, and interaction. The digital double uses real-time monitoring data (with the help of industrial Internet of Things technologies) to dynamically update the model [8]. At the same time, for the production cycle of ready-mixed concrete production and delivery, appropriate means of remote monitoring should also cover truck concrete mixers, which will provide reliable data about the events occurring at each stage of logistics in concrete delivery and calculate the necessary logistics efficiency indicators [9].

In addition, having huge volumes of historical data, it is possible to apply machine learning methods to analyze the orders of each client and determine patterns: when and at what time the client confirmed or canceled the order; what additional volume was ordered by the client; what is the probability of cancellation; how late was the transport or how long were the delays in loading or unloading. The overall goal of such analysis is to adjust production and transportation planning (preplanning) for future shifts and days: e.g., when more trucks are needed; where it is necessary to reduce the capacity of the car park; how to avoid idle trucks and excessive delays due to insufficient resources.

1.1. Motivation

The development and application of digital doubles is based on the description of behavior under various conditions of exploiting real materials, products, equipment, technological processes, and cyber-physical systems.

The digital double is based on a complex set of interrelated mathematical models with high adequacy to real objects and processes. In addition, the enterprise is represented not by a set of separate digital doubles but by a comprehensive simulation covering the entire production process.

Moreover, concrete plants must create a digital double, not only for production but also for logistics. Therefore, simulation models should consider integrating data from the production and transport systems system in real-time [10].

The above makes the creation and implementation of digital doubles at concrete plants relevant and important, which in turn its involves the development of a simulation model that covers all processes in the production and logistics of ready-mixed concrete.

1.2. State of the Art and problem statement

The concrete delivery problem is an optimization problem that investigates the optimal dispatch of trucks while satisfying some constraints related to time, demand, and resource availability [11].

Most published sources on the production of ready-mixed concrete mixtures are devoted to mathematical modeling and heuristic methods for reducing the impact of technological equipment breakdowns, improving operating costs, and optimizing product distribution [12]. The article [13] presented a simulation model for supplying and delivering ready-mixed concrete from three concrete plants to three construction sites to determine logistics cost and time. Unfortunately, the model developed in the AnyLogic modeling system is not flexible because a rigid structure of blocks represents it based on a discrete-event approach only for a certain number of concrete plants and construction sites. The article [14] discusses the issue of designing a digital double for a concrete mixed enterprise, which is used to predict process bottlenecks, anomaly detection, and failure prediction, along with additional capabilities for monitoring the productivity of the production process. An operational model of a digital twin for producing only one type of concrete was developed in the AnyLogic simulation system. This model reflects the production part of the process without touching logistics, which significantly limits the effectiveness of risk analysis in the concrete mix industry.

The study [15] considers the creation of a simulation model for the analysis of energy use and emissions into the environment. Several scenarios were under consideration, that is: a change in the productivity of concrete production; a change in the distance between the

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

plant and the construction site; and variation in the number and speed of movement of truck concrete mixers. However, the developed model of concrete supply is aimed at infrastructure with only one construction site, so it has a conditional benefit when researching real transportation tasks.

Some sources devoted to the production of ready-made concrete mixes are aimed at improving the quality of concrete and reducing costs. In [16], a model for predicting concrete quality was proposed based on the use of a genetic algorithm for the adaptive selection of functions based on predictive performance in the analysis of influencing factors, and a random forest method was used to correlate selected process characteristics with specific indicators of concrete quality. The previous study [17] presented a methodology for optimizing concrete mixtures by integrating machine learning and genetic algorithms. Machine learning models are used to predict the compressive strength of concrete, whereas genetic algorithms optimize mix cost under quality constraints. The solution to the problem of delivering ready-made concrete mixtures in the form of a multi-agent system based on the teamwork mechanism and the coordination of trucks was proposed in the article [18]. The authors deal with issues of decentralized dynamic planning of concrete delivery schedules. The environment of the truck agents' existence looks like a conditional space of a certain size, which thus complicates the mathematical apparatus for calculating routes and other parameters of the model and accordingly imposes many assumptions, which does not make it possible to consider the developed multi-agent model as a useful tool when solving real tasks of concrete delivery dispatch.

A mathematical regression model for predicting the productivity of concrete laying on a construction site after its delivery by truck-mounted concrete mixers from a concrete plant is considered in this paper [19]. Several factors affecting the efficiency of the concrete placing process are considered, for example, the productivity of the concrete plant, the number of truck concrete mixers that can work in a cycle, the distance between the construction site and the concrete plant, the amount of concrete delivered by truck concrete mixers to the construction site, and the number of workers involved, involved in laying concrete. A simulation model using the mathematical dependencies proposed by the authors was created using AnyLogic modeling software. However, the implementation of the model, as it follows from the work, is too conventional, with a rigid structure of the model that does not use all the advantages of the discrete-event combination or agent approaches and is designed for modeling only with one concrete plant and one construction site in mind.

The construction of a simulation model specifically for a network of concrete plants was considered in [20]. The operation of concrete plants is strongly influenced by the complex stochastic nature of concrete production and delivery processes; thus, the authors focused on the study of distribution laws to determine the time of production operations and transportation. The authors' approach is interesting, modeling concrete plants as those that jointly use trucks and transfer orders for concrete when unscheduled maintenance stops occur. It should be noted that most publications related to vehicle travel time planning are based on deterministic methods, including conditional travel times for any given distance, referring to urban transport norms. The authors, trying to move away from such an approach, proposed the use of a matrix that defines the laws of travel time distribution according to different ranges of the distance between the production and the object, as well as the time of day. However, despite this, the approach remains imperfect, especially since modern modeling tools allow connecting geoinformation systems and conducting simulations of real transport infrastructure.

The distribution of ready-mixed concrete has been considered in some publications as a purely problem of routing transportation means. In the study [21], a model for fuel consumption optimization for concrete mixers in a network of concrete plants was considered using an improved genetic algorithm. The model takes into account the influence of vehicle type, load, speed, and distance when building concrete delivery routes to minimize fuel consumption. A simulation model for solving the task of scheduling the delivery of ready-made concrete mix to construction sites was considered in the paper [22], where the authors applied an ant colony optimization algorithm. The task of modeling the logistics of ready-mix concrete delivery was solved in [23]. However, unfortunately, this study does not define the specifics of the model, the used supply policies, nor does it provide simulation results, which makes it impossible to assess the effectiveness and usefulness of the proposed model. A previous study [24] offers an optimization method based on mixed integer linear programming for planning delivery routes of ready-mixed concrete. The objective function formulas used by the authors of publications with linear programming problems represent the maximization of demand satisfaction, the minimum total travel time or distance, minimum operating costs, and the minimum idle time for both trucks and construction sites. However, some formulations do not match the complexity of a real problem or ignore important aspects of the problem, such as the time window and the time lag between deliveries. Thus, such models are usually developed for academic purposes; however, they are not relevant for real industrial applications.

1.3. Objectives and methodology

Therefore, despite the achievements in the research on the problem under consideration, there is still a lack of studies that comprehensively consider the technological processes of ready-mixed concrete mixture production and logistics.

Thus, the study aims to create a simulation model of the production and delivery of ready-mixed concrete in a network of manufacturing plants and construction sites, as part of a project to create a digital double for making effective risk management decisions in real time for the early detection of suboptimal activity in the production of commercial concrete mixture and logistics. Following the stated aim of the research, it is necessary to consider the following objectives:

1. To analyze the problems and features of creating digital doubles in the production and logistics of concrete plants.
2. To develop a simulation model for analyzing the production processes and logistics of ready-made concrete mixtures.
3. To provide an illustrated example of modeling production and logistics processes in a network of concrete factories and construction sites.
4. To conduct optimization experiments in order to determine the modes of operation of the system.

To analyze the production processes and logistics of concrete plants, methods and models are used: system analysis, and agent simulation modeling.

This paper has the following structure. Section 2 provides a detailed overview of the features for creating digital doubles in the production and logistics of concrete plants. Section 3 describes a simulation model for analyzing production processes and logistics of ready-mixed concrete mixtures. Section 4 presents the evaluation and results of modeling the production and logistics processes of ready-mixed concrete and provides a detailed overview of the user interface. Section 5 discusses the findings, and contains details about the optimization experiments on the simulation model. Section 6 summarizes the key contributions and outlines potential directions for future research.

2. Analysis of the features for creating a digital double in the production and logistics of concrete plants

It should be noted that the main method of planning the production of ready-mix concrete is Just-in-Time (JIT), which is used precisely because of the rapid perishability of the final product. The lifetime of ready-mixed concrete should not exceed 2-3 hours from the moment of production at the factory to its use on the construction site, and this is subject to continuous mixing in the mixer barrel of special vehicles—truck concrete mixers [25]. The production process itself (Fig. 1) consists of supplying raw materials, batching concrete, mixing concrete, loading chemicals/admixtures, and unloading concrete onto trucks for delivery to the construction site.

This mode of planning potentially ensures that the customer receives products on time, at the right quality, and at the right quantity, thereby reducing on-site losses and increasing process productivity. Any slight delay in production can cause delivery delays; therefore, it is important to apply a risk response method to prevent such production disruptions.

A digital double (model) is built on historical data that has been cleaned and processed. In real-time, the digital model analyzes the incoming data and registers the discrepancies between the actual and expected values (Fig. 2). A key element of digital twin technology in logistics is the centralization of all planning and dispatch divisions. Instead of independent planning at the local level, centralization unlocks the synergy of planning and management for the entire network of concrete plants, factories, warehouses, and construction sites.

Thus, reducing the time when the mixture is not mixed and loaded into delivery trucks, as well as pouring at the client’s place, is always a bottleneck in the overall process of concrete supply, and it is highly dependent on various risks. Fig. 3 shows the main directions and risk factors that should be considered in the business process of production and delivery of ready-mixed concrete.

It can be inefficient planning of the operation of concrete mixing equipment and the delivery itself, queues or errors during loading, long idle times waiting for pouring at construction sites, inconsistency of actions with the client, transport being late for loading or unloading, suboptimal delivery routes, deviations from the route during delivery, etc. In the end, all this leads to the violation of production plans, which leads to the incomplete use of the plant's capacity, and as a result, productivity decreases. A strategy to increase productivity for a concrete manufacturer can certainly be the purchase and deployment of new concrete mixing equipment and transport to meet the increased volume of orders; however, this is a significant investment and quite risky, given the dynamics of the market. Therefore, it is possible to increase overall productivity of ready-mixed concrete enterprises quickly and with minimal cost due to the introduction of modern information technologies following the requirements of Industry 5.0 and an increase in delivery productivity. Concrete plants have the potential to increase their productivity by minimizing downtime during working hours.

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

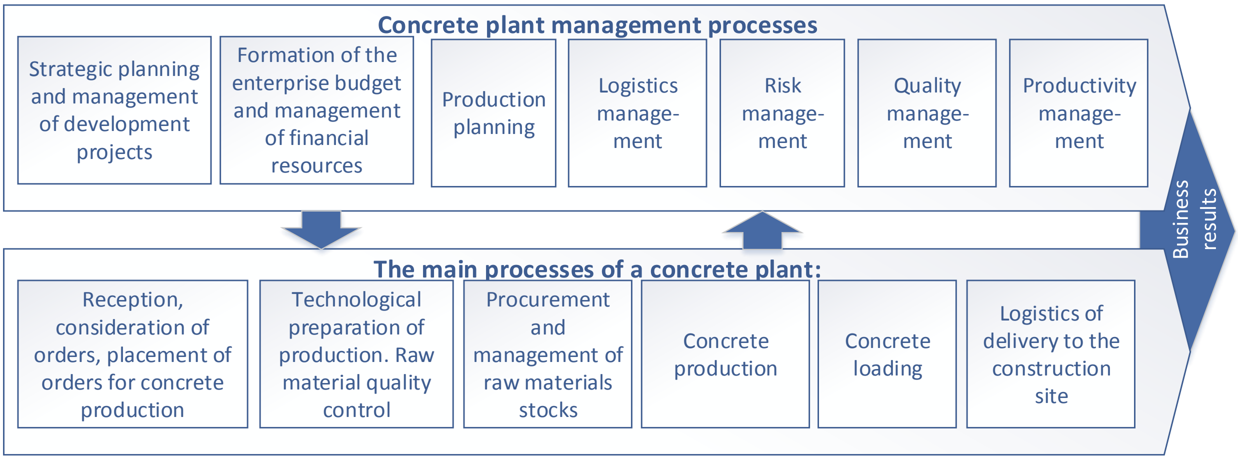

Fig. 1. Manufacturing and management processes of a concrete plant

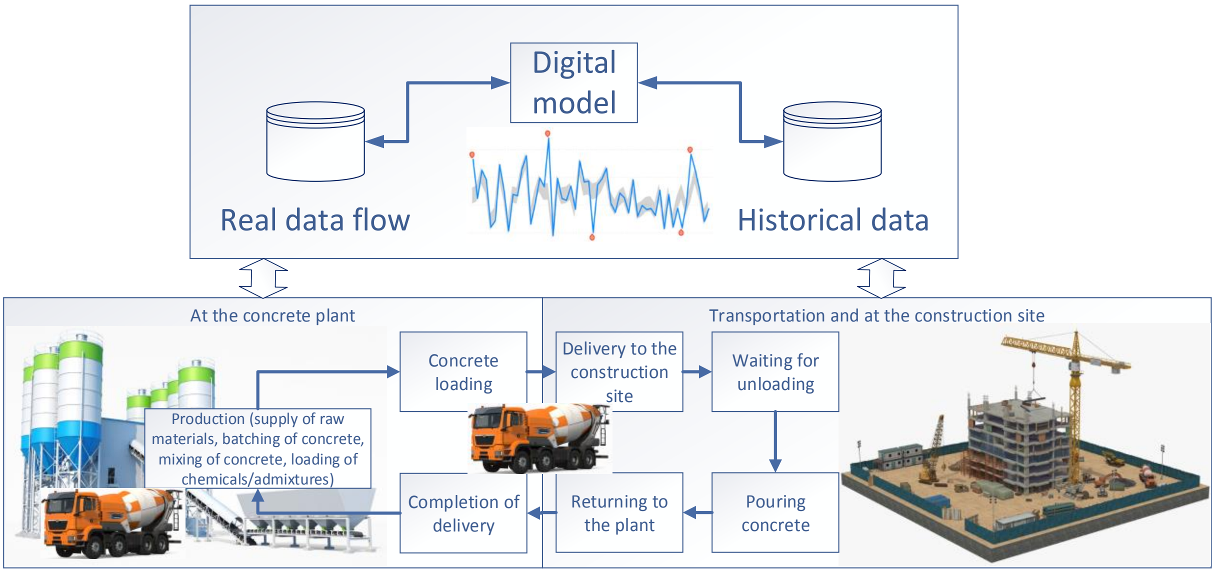

Fig. 2. A digital double in the production and logistics of a concrete plant

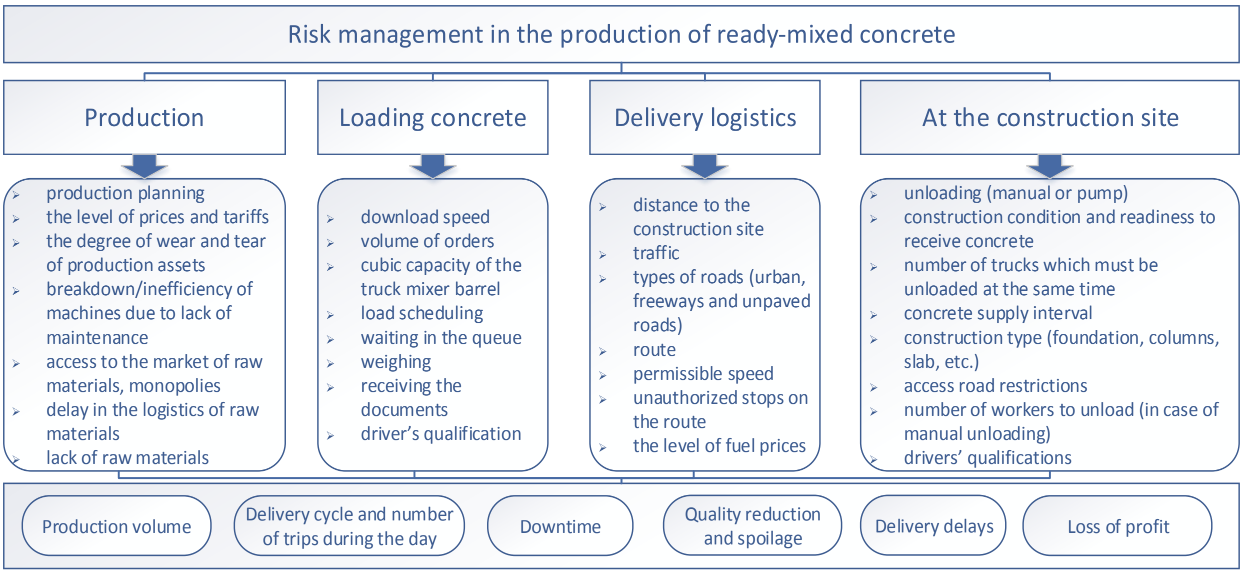

Fig. 3. Risk management in the production of ready-mixed concrete

The construction industry is already experiencing value in managing risks and increasing efficiency in the way it executes projects using Industry 5.0 technologies such as digital twins, industrial Internet of Things, and digital modeling [26, 27]. Thus, it is proposed to implement development projects for ready-mixed concrete enterprises based on digital doubles. The two key elements of a digital double are a dynamic simulation model and data reflecting the current state of the real system [28].

Thus, the implementation of a project to create a digital double at a concrete plant solves the same problems: monitoring the productivity of the production process and logistics of concrete delivery; predictive analytics to identify bottlenecks in production and logistics processes; reducing plant and customer downtime; predictive maintenance of equipment, optimizing maintenance resources; and improving asset performance and productivity. If a ready-mixed concrete enterprise begins to automate the processes of production and organization of delivery, making them transparent, then there is an immediate opportunity to influence most factors of the delivery cycle and reduce the time of each stage, which in turn leads to increased productivity.

3. A simulation model for analyzing production processes and logistics of ready-mixed concrete mixtures

To fully consider all interdependencies, limitations, dynamics, and uncertainties, a simulation model was created that covers all processes in the production and logistics of ready-mixed concrete.

The simulation model was developed in an AnyLogic environment [29, 30] and consists of components, each of which reflects a separate element of the dynamics of the enterprise's behavior and the concrete distribution infrastructure. The AnyLogic system was chosen due to its support and ability to hybridize different types of simulation models, the availability of the necessary pre-configured elements for modeling production and transport systems, and support for a geo-information system for automatic routing on real roads.

When developing the model, various aspects that make up the problem of concrete delivery were considered, such as the following:

1) orders are extremely unpredictable and changeable because many orders occur on the same day, which requires modeling of the intensity of delivery, both according to the client's schedule and by chance;

2) the manufacturer must over-order by approximately 20% to compensate for the unpredictability of the customers' order flow;

3) most orders require synchronized deliveries by several trucks, which affects the determination of the available fleet capacity;

4) the travel time between the production enterprise and construction site in our model is determined using a geo-information system with real transport infrastructure. The number and location of concrete plants and construction sites are specified in the database, which allows modeling any type of network without the need to make changes to the model;

5) the duration of work on pouring concrete at the construction site is modeled considering different resource settings;

6) the period during which concrete must be delivered to the client is monitored and statistics are recorded on orders where the delivery deadline has been violated;

7) the type of concrete ordered by the client is taken into account, which in turn requires a table of preparation recipes. For flexibility, this information is loaded from the database.

In the developed simulation model, using the class of active objects (agents), the following aspects are implemented: plant; order; construction site; specification for concrete; truck concrete mixer. Each agent has its own variables and a mathematical model describing its behavior. For example, a client agent is characterized by the following parameters: type; number of jobs; sales volume; load size; distance to the plant; level of service; the number of unloading workers. In addition, it is possible to determine the number of agents, for example, the size of the fleet or the number of construction sites.

The agent of the concrete plant is represented by a discrete-event model of the production process (dosing of concrete components according to the recipe to order the right type of product, mixing concrete, and adding chemicals/admixtures) and has a fleet of trucks. It is characterized by the output of concrete production, the work schedule, the size of bunkers and containers for storing materials, the level of the insurance stock for materials available, and the number of truck concrete mixers. Accordingly, the problem of planning schedules for the supply of raw materials (cement, sand, crushed stone, water, and admixtures) is solved at the same time.

A concrete plant order portfolio is formed by receiving and reviewing requests from construction sites. The ordering agent provides information about the concrete delivery location (construction site), the type and quantity of concrete to be delivered, and the desired start time (first delivery). This allows the agent of the concrete plant to accept or reject the request, considering the productivity of the production facilities. In addition, the order agent has parameters to accumulate statistics regarding the life cycle of order execution and its status. The truck agent is characterized by its belonging to a specific concrete plant, the volume of the barrel, the

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

speed of movement on the roads, the agent of the order it fulfils, as well as the parameters of the accumulation of statistics, namely: waiting time for loading, loading time, transportation time to the customer, waiting time for unloading at the customer's, unloading time, return time to the plant, number of trips, etc. Once loaded, the truck cannot serve multiple construction sites and must return to the plant after delivery. The data accumulated in the course of simulation always provides an opportunity to see the state in which the truck is moving, the waiting time for loading, the time for concrete delivery to customers, the waiting time for unloading, etc.

The agent of the construction site initiates the creation of a new order for delivering concrete of the specified type, volume, and delivery terms. Construction sites are served by the nearest concrete plant. The agent implements a discrete-event model that describes the operations related to the reception, unloading, and concrete placement of trucks and the additional maintenance of concrete mixer trucks (cleaning). Resources in the form of concrete pumps and workers, their work schedule, and the type of unloading are also being taken into account. According to the simulation results, statistics are accumulated regarding the fulfilment of orders and the actual delivery of concrete, the employment of resources for unloading, the waiting time for unloading, indicators of the truck queue for maintenance, etc.

Our model is essentially a combination of different modeling methods. Discrete-event modeling is used to describe production processes at the plant and the process of unloading concrete mixer trucks and placing concrete on the construction site, system dynamics for the formation of material stocks at concrete plants, and the agent approach, where plants, construction sites, trucks, and orders are agents with autonomous behavior and the ability to scale in the population of the required amount.

Fig. 4 shows the model after launch. Agents live in the geographic information system. The names of the initial locations of the production facilities and distributors were extracted from the database. The search engine of the geographic information system is used to search for places on the map and for place agents there.

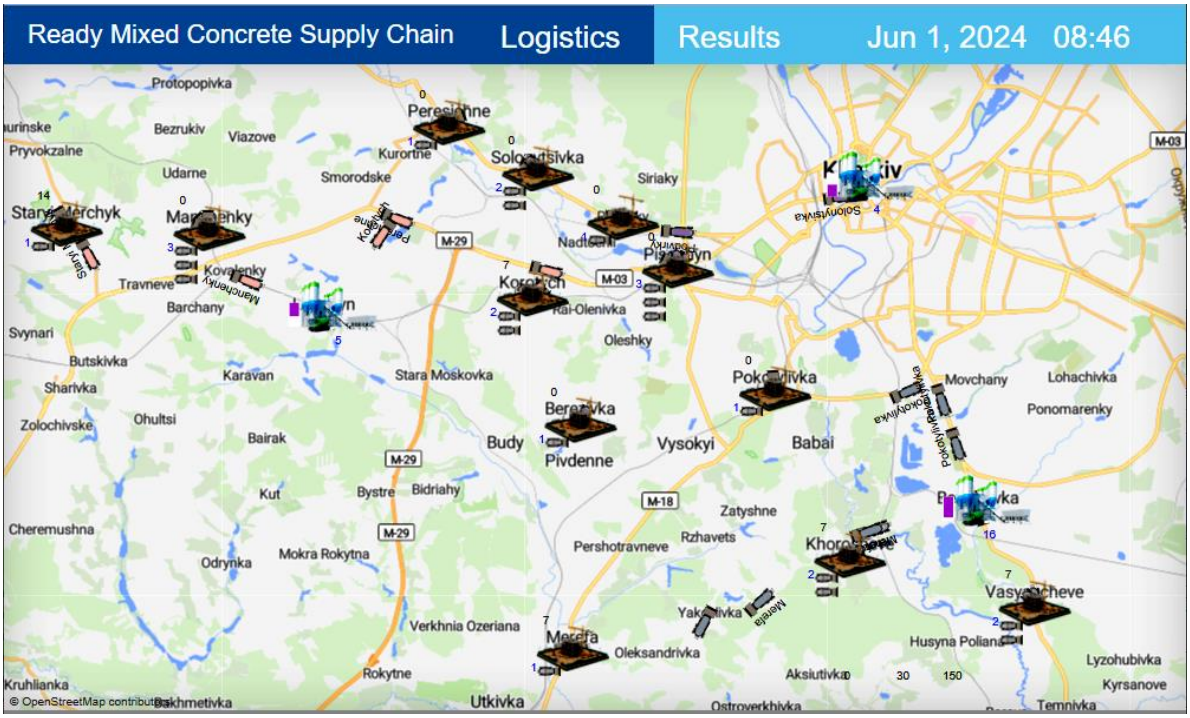

Fig. 4. Animated simulation of concrete delivery in a network of concrete plants and construction sites

Estimated travel time is an important input parameter for preliminary transport risk assessment (concrete mixing time, etc.). However, thanks to the use of the built-in routing module in the AnyLogic geoinformation system, the system always chooses the shortest route for the entire network from the OpenStreetMap service. Trucks move on real roads, and routes are created when vehicles start moving along their routes. Near each of the concrete plants, a histogram showing the volume of concrete produced and a quantitative indicator of free trucks can be observed. Near the construction site, we can see the quantitative value of the concrete delivered during the entire time, and the icons of the trucks on the site waiting for unloading. Clicking on the objects in production and construction displays the simulation results. The model is animated; thus, you can observe the movement of trucks along realigning transport infrastructure and not along hypothetical routes or conventionally set distances, as presented in most studies on this topic.

4. An example of modeling the production and logistics processes of ready-mixed concrete

In our example, the model simulates the concrete delivery to the Kharkiv region. The supply chain includes three manufacturing facilities and 12 construction sites that order random quantities of a given type of product every 1-2 days. Each concrete plant has a fleet of concrete mixers, the number of which can be changed at the beginning of the simulation and during the process.

Each concrete plant uses a certain number of concrete mixer trucks of different volumes. When the plant receives an order from a construction site, it checks the balance from the current orders. If the required quantity of a given type is available, the plant sends a loaded truck to the customer.

Otherwise, the order is queued until the plant completes the product. The rule for choosing a place for concrete delivery is determined by different strategies, for example, according to the priority of the place, and then according to the minimum idle time of the construction site and the minimum idle time of the concrete mixer truck.

The production process is determined by the technological operations inherent in concrete plants, considering the available material stocks and the productivity of the equipment. A queue of truck-concrete mixers is formed before loading concrete at each plant. After the concrete mixer truck is loaded, it leaves the plant and goes to the specified construction site. When a concrete mixer truck arrives at a customer's premises, it joins a FIFO priority queue, which ensures that the first concrete mixer truck to arrive is also the first to be unloaded. After unloading the concrete mixer, the mixer leaves the site and returns to its plant.

During simulation, the process can be displayed using various representations, such as parameters, variables, diagrams, and graphs.

Fig. 5 presents a screen with the results generated for a separate concrete plant. Observing the modeling process, you can see the main indicators of orders and production, current stocks of materials and the dynamics of their consumption and deliveries, concrete production in quantitative indicators and in the dynamics of production/shipment, the employment of the concrete mixer fleet, the queue of orders from customers, a list of cargo shipments to customers with an indication of the status (on time/late), a histogram of the product distribution, waiting time, and transportation time. In addition, elements were added to vary the parameters of the plant's productivity and the size of the truck fleet.

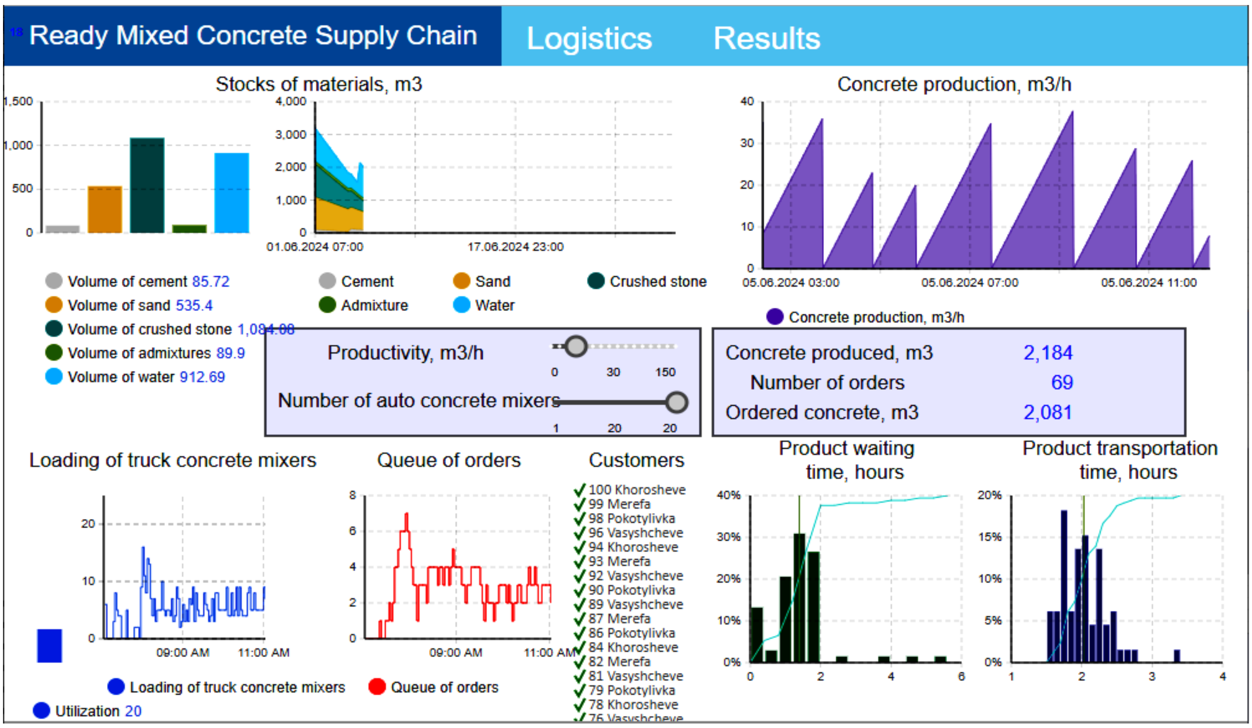

Fig. 5. Simulation results for a concrete plant

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

Fig. 6 presents a visualization of the simulation results for a construction site. Observing the modeling process, the main indicators and schedules for concrete orders and deliveries, the employment of unloaders, a histogram of the waiting time for unloading distribution, and the number of truck concrete mixers waiting for unloading. During the simulation, you can conduct experiments by varying the intensity of the orders from the construction site.

Fig. 7 shows a screen displaying the results for one of the truck concrete mixers.

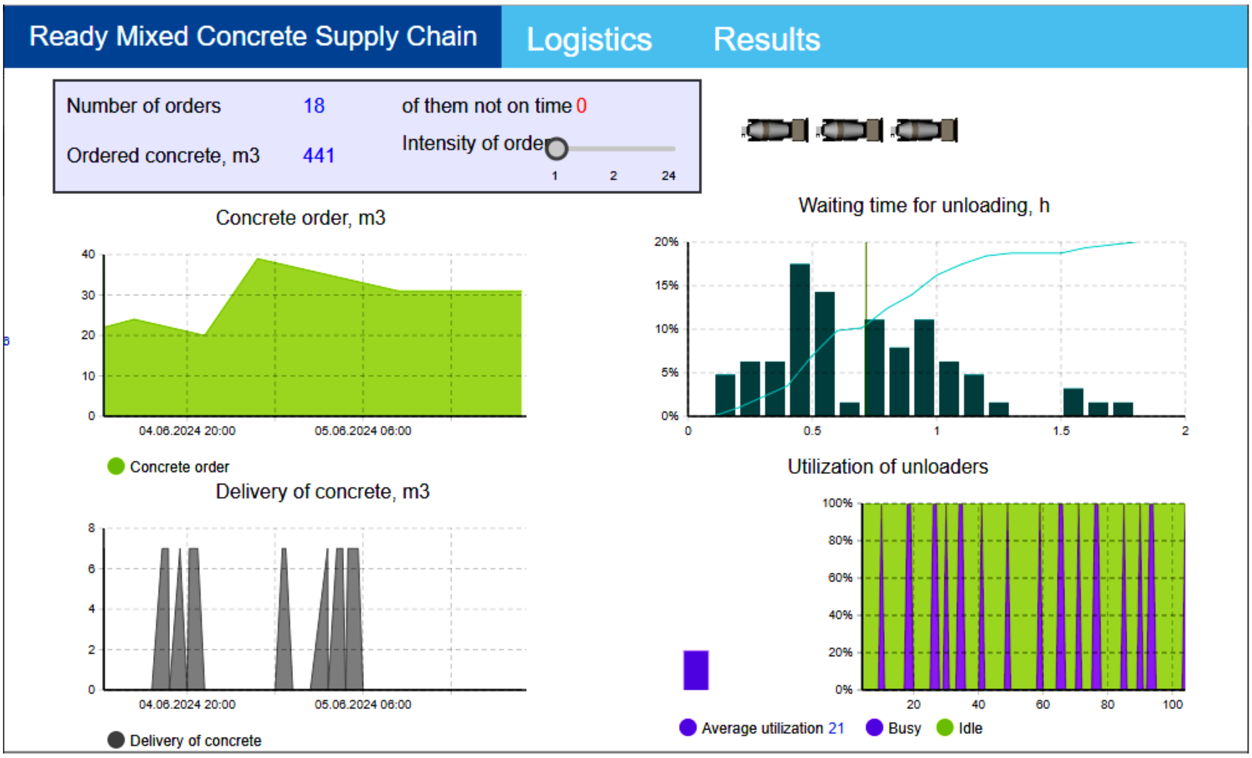

Fig. 6. Simulation results for a construction site

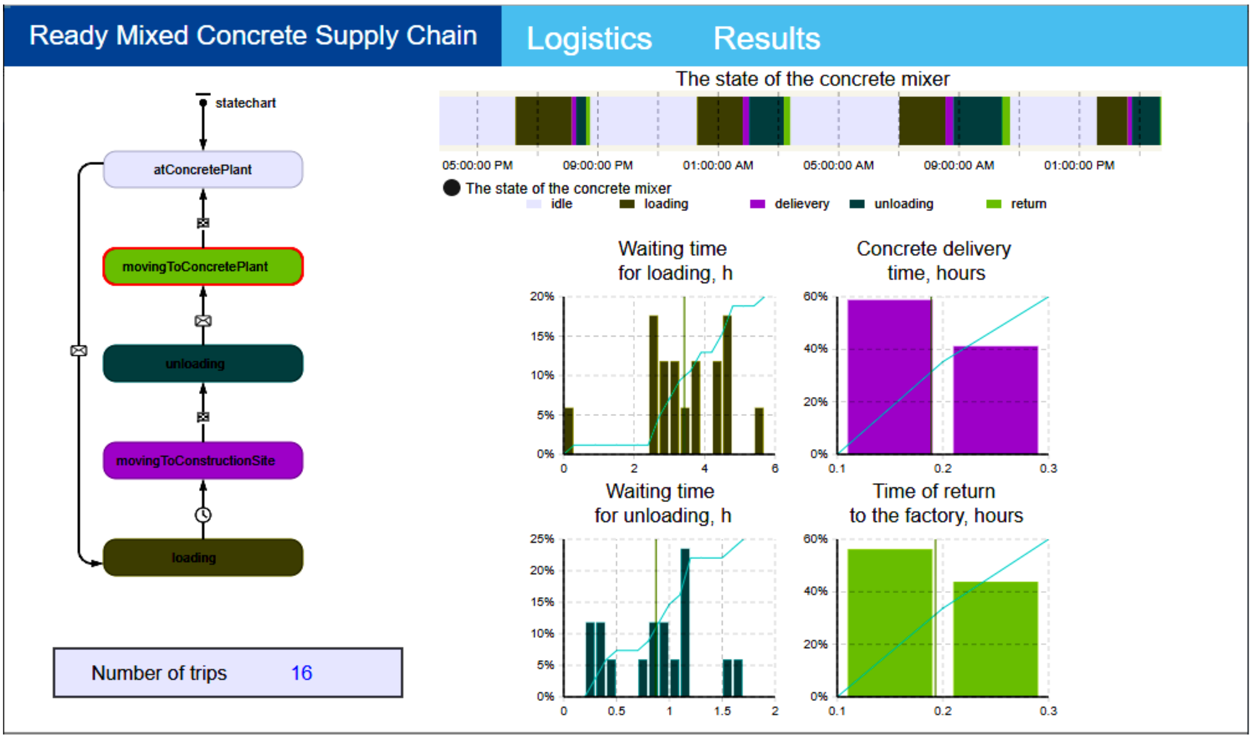

Fig. 7. Simulation results for a concrete mixer truck

Observing the modeling process, you can see a diagram of the truck condition, a Gantt chart with the start and end dates of operations, and histograms of the waiting times for loading, unloading, delivering concrete to customers, and returning to the plant. In addition, in this figure, you can directly see the condition diagram, which determines the behavior of the concrete mixer truck agent. The diagram includes the following conditions: at the plant, on loading, on the way to the customer, waiting for unloading at the construction site, and returning to the plant.

For each transition between states, corresponding triggers are set that are associated with receiving messages from other agents and parts of the process model. Due to the stochastic nature of the truck delivery and maintenance process, the durations of specific parts of the process, which are random variables, are represented by their probability distributions.

Fig. 8 presents aggregated results for the entire network of concrete plants, where the current indicators of concrete production, production dynamics, fleet employment, and product waiting time.

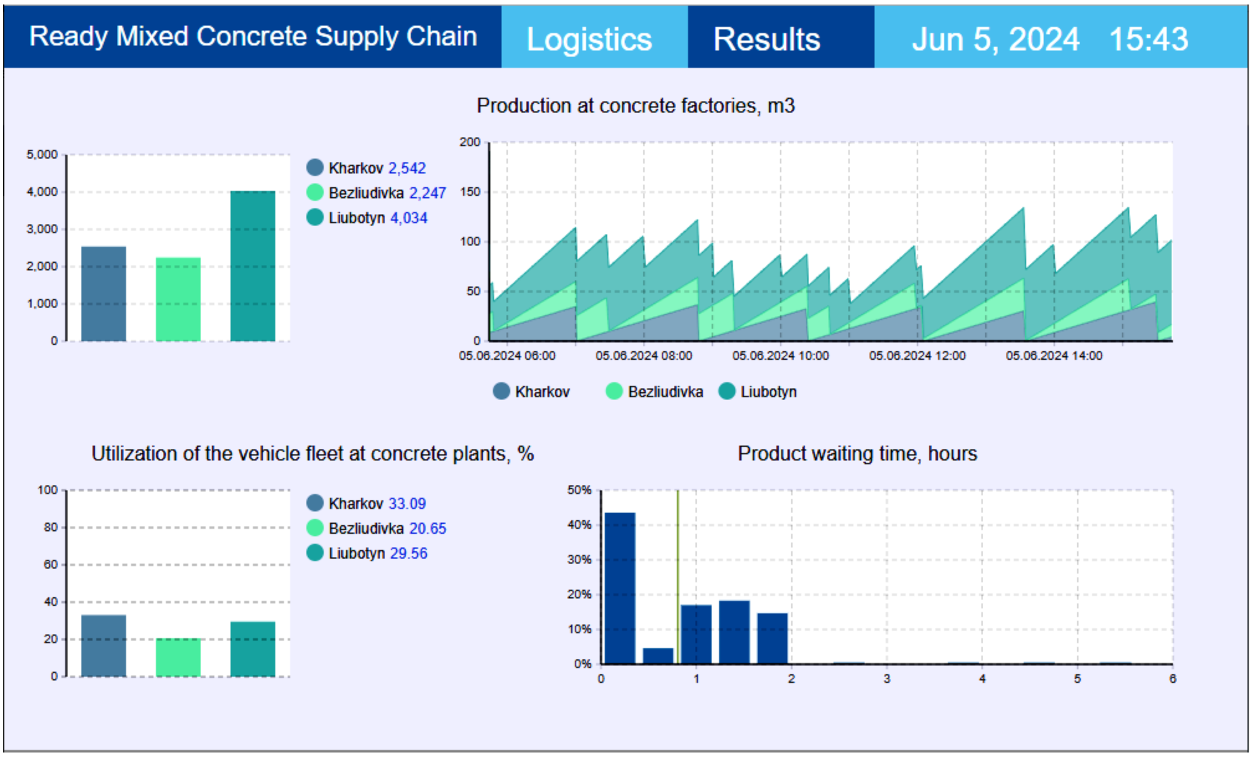

Fig. 8. Results for the network of concrete plants

Thus, during the simulation, the volumes of concrete produced at all factories and the volumes of concrete delivered to construction sites were summed. When the amount received is equal to the demand at the construction site or the capacity of a particular plant, the construction site or plant temporarily stops production or delivery until new orders appear.

5. Discussion

Experiments were conducted to test and verify the proposed simulation model. The verification of the model involves formally verifying the accuracy of its operation with given data obtained from industry experts. The model results are more sensitive to changes in some data and less sensitive to changes in other data.

Planning transport operations for the delivery of ready-mixed concrete requires selecting an optimal or near-optimal solution to maximize economic benefits. The shortest way to improve the efficiency of concrete plant logistics management is to adopt the most economical and environmentally friendly choice due to the consumption of the minimum amount of fuel and the reduction of emissions for concrete mixer trucks.

Different scenarios were formed to establish optimal requirements for the functioning parameters of the system elements. This necessity is determined by the planned volume for a certain day and the relevance of order delivery. Sensitivity analysis was performed on some variables, i.e., order flow, plant productivity, shipped volumes, and available concrete mixers, to determine the impact on concrete supply compliance. These results made it possible to estimate the number of automixers needed to fulfill orders and the capacity utilization rate of production facilities under a certain level of maintenance.

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

Fig. 9 shows the optimization results by maximizing the coefficient of using automatic concrete mixers. The following parameters varied and, as a result, were limited: the productivity of the concrete plants, the number of truck concrete mixers, and the product waiting time.

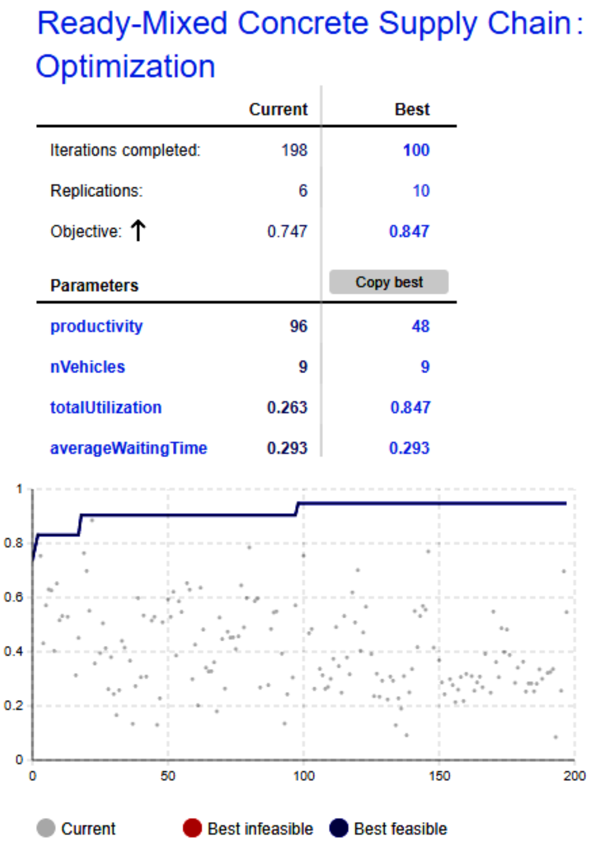

Fig. 9. Results of optimization by maximizing the coefficient of using truck concrete mixers

The results demonstrate the achievement of the employment rate of concrete mixers at the level of 85% when using 9 concrete mixers. The productivity of the plant is 48 m^3/h, and the average waiting time for the concrete mixers for the product according to the given order intensity is 0.3 hours.

Fig. 10 visualizes the results of optimization by minimizing the waiting time for the concrete mixer product. The following parameters varied and thus were limited: the productivity of the concrete plants, the number of truck concrete mixers, and the coefficient of using truck concrete mixers.

The results demonstrate the achievement of the value by minimizing the product waiting time for concrete mixers at the level of approximately 5 min with the use of 12 concrete mixers, plant productivity of 73 m^3/h and 64% utilization ratio of concrete mixers.

The simulation model developed in the example attempts to optimize the process of simultaneous delivery of ready-mixed concrete to twelve construction sites from three concrete plants by minimizing the time (as well as the cost) of the downtime for the truck concrete mixers and the time (as well as the cost) of the downtime of the concrete mixer pumps on the construction site. For this purpose, various combinations of the considered modeling parameters were applied, and the obtained experimental results were verified.

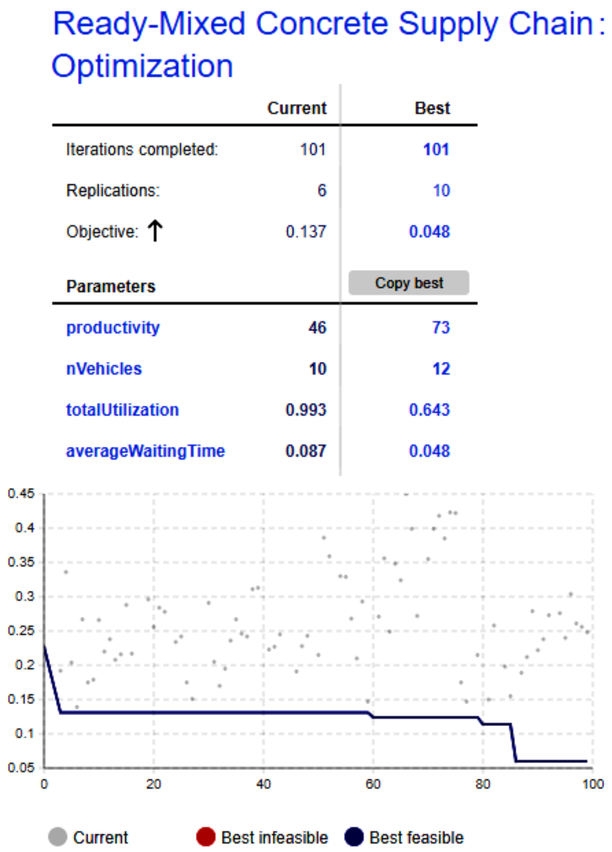

Fig. 10. Results of optimization by minimizing the waiting time of the concrete mixer products

The proposed simulation model can be useful at the planning stage and allows more accurate prediction of the duration and modes of work during production operations at concrete plants, delivery of products to consumers, and, thus, can influence decision-making, forecasting progress of work, and better management of production and logistics processes, to increase productivity, reducing downtime, and total costs. The generated optimization and simulation model can be a useful tool that can help managers, dispatchers, and engineers of both concrete plants and construction sites plan the work performance.

The model was able to evaluate system options from the perspective of necessary capital investments (purchase and maintenance of the vehicle fleet) with efficient use of resources and maintaining a high level of service, which represents additional value for clients. The service level varies depending on the number of available concrete mixer trucks and the specified shipment volume. It is important to emphasize that as the level of service and maintenance increases, each additional concrete mixer included in the system provides a slight increase in the delivery compliance rate, but it costs a lot, which is justified by the fairly constant demand for products, which unfortunately still varies throughout the Ukrainian territory.

6. Conclusions

A study of the multi-criteria decision-making support task for the effective management of ready-mix concrete production and its delivery to construction sites, considering risk factors, was conducted. Considering our research findings, we have drawn the following conclusions.

1. The analysis of the problems and features of creating digital doubles in the production and logistics of concrete plants showed that it is important for concrete plants to create digital doubles not only for production but also for logistics, where the appropriate means of remote monitoring should also cover concrete mixer trucks, which will ensure reliable data about what happens at each stage of concrete delivery logistics and calculate the necessary logistics performance indicators.

2. A simulation model of analyzing production processes and logistics of ready-mixed concrete mixtures in the AnyLogic system was developed. The model is created as a combination of different modeling methods, i.e., discrete-event modeling is used to describe production processes at the plant and the process of unloading concrete mixers and placing concrete at construction sites; system dynamics – for the formation of material stocks at concrete plants; agent modeling because plants, construction sites, trucks, and orders are agents with autonomous behavior and the possibility of scaling up the population of the required amount. Each agent has variables and a mathematical model that describes its behavior. The model includes technological processes in the production and logistics of ready-made concrete mixtures: supply of raw materials; dosing of concrete; concrete mixing; loading of chemicals/admixtures; formation of a concrete mixer truck queue at a concrete plant; loading in a truck concrete mixer; route to the construction site; queues of truck concrete mixers at the construction site; unloading of truck concrete mixers at the construction site; and return of truck concrete mixers to the concrete plant.

3. An illustrated example of modeling production and logistics processes in a network of concrete plants and construction sites is provided. According to the simulation results, statistics are accumulated: the cost structure separately (production, transportation, pouring, idle cost) for each construction object, as well as in total for all construction objects; the number of concrete mixer trucks for each plant; the amount of manufactured /poured concrete for each installation/site; the duration of loading/unloading/idling; the average time in the queue, etc. The time on the road for concrete mixer trucks is determined by using a geographic information system, including real transport infrastructure, which distinguishes this study from most existing ones.

4. Optimization experiments were performed to determine the modes of the system operation. This paper presents two experiments to maximize the utilization rate of concrete mixers and minimize the waiting time of concrete mixers for the product. In general, there are more developed scenarios for use by company managers, dispatchers, and engineers at concrete plants and construction sites when planning work.

Future research will be aimed at the implementation of scenarios for the combined use of truck-concrete mixers in the network, which means that it is not necessary to return the truck-concrete mixer to the concrete plant from which it started its working shift. It is also planned to simulate possible failures and breakdowns of technological equipment and truck concrete mixers to find the optimal balance of supply/transportation costs under these conditions and to prevent disruption of production plans or incomplete use of production capacities.

Contribution of authors: simulation model of the analysis of production processes and logistics of concrete plants, analysis of the results of modeling and design of the manuscript – **Mikhailo Buhaievskyi**; analysis of problems and features of creating digital doubles in the production and logistics of concrete plants – **Yuri Petrenko**.

Conflict of interest

The authors declare that they have no conflict of interest concerning this research, whether financial, personal, authorship, or otherwise, that could affect the research and its results presented in this paper.

Financing

The research was conducted without financial support.

Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence methods while creating the current work.

All the authors have read and agreed to the published version of this manuscript.

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

References

1. Fitriani, H., & Rizki, L. D. Just-in-time application on readymix concrete production. *International Journal of Advanced Technology and Engineering Exploration*, 2022, vol. 9, pp. 1183-1195. DOI: 10.19101/IJATEE.2021.876116.

2. Khan, M.A., Deep, S., Asim, M., Khan, Z.R. Quantization of Risks Involved in Supply of Ready Mix Concrete in Construction Industry in Indian Scenario. *International Journal of Civil Engineering and Technology*, 2017, vol. 8, iss. 3, pp. 175-184. Available at: http://www.iaeme.com/IJCIET/issues.asp?JType=IJCIET&VType=8&IType=3. (accessed 12.04.2024).

3. Chen, S., Ye, Z., Lu, W., & Feng, K. Exploring Performance of Using SCM Concrete: Investigating Impacts Shifting along Concrete Supply Chain and Construction. *Buildings*, 2024, vol. 14, article no. 2186. DOI: 10.3390/buildings14072186.

4. Pronchakov, Y., Prokhorov, O., & Fedorovich, O. Concept of High-Tech Enterprise Development Management in the Context of Digital Transformation. *Computation*, 2022, vol. 10, iss. 7, article no. 118. DOI: 10.3390/computation10070118.

5. Ding, C., Liu, H., Chen, Y., & Qiu, W. Collaborative Innovation in Construction Supply Chain under Digital Construction: Evolutionary Game Analysis Based on Prospect Theory. *Buildings*, 2024, vol. 14, article no. 2019. DOI: 10.3390/buildings14072019.

6. Nour El-Din, M., Pereira, P. F., Poças Martins, J., & Ramos, N. M. M. Digital Twins for Construction Assets Using BIM Standard Specifications. *Buildings*, 2022, vol. 12, article no. 2155. DOI: 10.3390/buildings12122155.

7. Shahzad, M., Shafiq, M.T., Douglas, D., & Kassem, M. Digital Twins in Built Environments: An Investigation of the Characteristics, Applications, and Challenges. *Buildings*, 2022, vol. 12, article no. 120. DOI: 10.3390/buildings12020120.

8. Dinter, R., Tekinerdogan, B., & Catal, C. Predictive maintenance using digital twins: A systematic literature review. *Information and Software Technology*, 2022, vol. 151, article no. 107008. DOI: 10.1016/j.infsof.2022.107008.

9. Moshood, T. D., Nawanir, G., Sorooshian, S., & Okfalisa, O. Digital Twins Driven Supply Chain Visibility within Logistics: A New Paradigm for Future Logistics. *Applied System Innovation*, 2021, vol. 4, article no. 29. DOI: doi.org/10.3390/asi4020029.

10. Mehmood, S., Fan, J., Dokota, I.S., Nazir, S., & Nazir, Z. How to Manage Supply Chains Successfully in Transport Infrastructure Projects. *Sustainability*, 2024, vol. 16, article no. 730. DOI: 10.3390/su16020730.

11. Tzanetos, A., & Blondin, M. Systematic search and mapping review of the concrete delivery problem (CDP): Formulations, objectives, and data. *Automation in Construction*, 2023, vol. 145, article no. 104631. DOI: 10.1016/j.autcon.2022.104631.

12. Olugboyega, O., Ejohwomu, O., Omopariola, E. D., & Omoregie, A. Sustainable Ready-Mixed Concrete (RMC) Production: A Case Study of Five RMC Plants in Nigeria. *Sustainability*, 2023, vol. 15, article no. 8169. DOI: 10.3390/su15108169.

13. Matejević-Nikolić, B., & Živković, L., Development of the Simulation Model for Ready Mixed Concrete Supply Chain Cost Structure. *Tehnički vjesnik*, 2023, vol. 30, iss. 1, pp. 102-113. DOI: 10.17559/TV-20220310120002.

14. Weerapura, V., Sugathadasa, R., De Silva, M. M., & Nielsen, I. Feasibility of Digital Twins to Manage the Operational Risks in the Production of a Ready-Mix Concrete Plant. *Buildings*, 2023, vol. 13, article no. 447. DOI: 10.3390/buildings13020447.

15. Nellickal, A. G., Rajendra, A. V., & Palaniappan, S. A simulation-based model for evaluating the performance of ready-mixed concrete (RMC) production processes. *Living and Learning: Research for a Better Built Environment: 49th International Conference of the Architectural Science Association* 2015, pp. 658–667. Available at: https://anzasca.net/wp-content/uploads/2015/12/063_Nellickal_Rajendra_Palaniappan_ASA2015.pdf. (accessed 12.04.2024).

16. Xu, J., Zhou, L., He, G., Ji, X., Dai, Y., & Dang, Y. Comprehensive Machine Learning-Based Model for Predicting Compressive Strength of Ready-Mix Concrete. *Materials*, 2021, vol. 14, article no. 1068. DOI: 10.3390/ma14051068.

17. Oviedo, A. I., Londoño, J. M., Vargas, J. F., Zuluaga, C., & Gómez, A. Modeling and Optimization of Concrete Mixtures Using Machine Learning Estimators and Genetic Algorithms. *Modelling*, 2024. vol. 5, pp. 642-658. DOI: 10.3390/modelling5030034.

18. Matejević-Nikolić, B., & Živković, L. Comparative Representation of Two Models for Predicting the Productivity of Column and Wall Concreting Process. *Buildings*, 2022, vol. 12, article no. 1809. DOI: 10.3390/buildings12111809.

19. Hanif, S., Din, S. U., Gui, N., & Holvoet, T. Multiagent Coordination and Teamwork: A Case Study for Large-Scale Dynamic Ready-Mixed Concrete Delivery Problem. *Mathematics*, 2023, vol. 11, article no. 4124. DOI: 10.3390/math11194124.

20. Sanchez, J., & Aristizabal, M. Simulation a ready-mix concrete plants network using multimethod approach. *Proceedings of the 2017 Winter Simulation Conference*, 2017, pp. 2405-2412. Available at: https://www.researchgate.net/publication/322212507_SIMULATION_A_READY-MIX_CONCRETE_

PLANTS_NETWORK_USING_MULTIMETHOD_APPROACH. (accessed 12.04.2024).

21. Yang, J., Zhu, H., Ma, J., Yue, B., Guan, Y., Shi, J., & Shangguan, L. Improved Genetic Algorithm for Solving Green Path Models of Concrete Trucks. *Applied Sciences*, 2023, vol. 13, article no. 9256. DOI: 10.3390/app13169256.

22. Choi, J., Xuelei, J., & Jeong, W. Optimizing the Construction Job Site Vehicle Scheduling Problem. *Sustainability*, 2018, vol. 10, article no. 1381. DOI: 10.3390/su10051381.

23. Mustakim, M., Rohafiz, S., Khairiel, A.N., Adebare, O., & Alonge, O. An Innovative of Simul Model for Ready-Mix Concretes in the Concept of Third-Party Logistics and Supply Chain Management in Malaysia and Thailand. *International Journal of Supply Chain Management*, 2020, vol. 9, iss. 5, pp. 908-914. Available at: https://ojs.excelingtech.co.uk/index.php/IJSCM/article/viewFile/5187/2815. (accessed 12.04.2024).

24. Syahputra, R. H., Komarudin, K., & Destyanto, A. R. Optimization Model of Ready-Mix Concrete Delivery Route and Schedule: A Case in Indonesia RMC Industry. *3rd International Conference on Computational Intelligence and Applications (ICCIA)*, Hong Kong, China, 2018. pp. 21-25. DOI: 10.1109/ICCIA.2018.00012.

25. Arularasi, V., Pachiappan, T., Avudaiappan, S., Raman, S. N., Guindos, P., Amran, M., Fediuk, R., & Vatin, N. I. Effects of Admixtures on Energy Consumption in the Process of Ready-Mixed Concrete Mixing. *Materials*, 2022, vol. 15, article no. 4143. DOI: 10.3390/ma15124143.

26. Hakimi, O., Liu, H., Abudayyeh, O., Houshyar, A., Almatared, M., & Alhawiti, A. Data Fusion for Smart Civil Infrastructure Management: A Conceptual Digital Twin Framework. *Buildings*, 2023, vol. 13, article no. 2725. DOI: 10.3390/buildings13112725.

27. Coito, T., Faria, P., Martins, M. S. E., Firme, B., Vieira, S.M., Figueiredo, J., & Sousa, J. M. C. Digital Twin of a Flexible Manufacturing System for Solutions Preparation. *Automation*, 2022, vol. 3, pp. 153-175. DOI: 10.3390/automation3010008.

28. Prokhorov, O., Pronchakov, Y., & Prokhorov, V. Cloud IoT Platform for Creating Intelligent Industrial Automation Systems. *Lecture Notes Network Systems*, 2021, vol. 188, pp. 55–67. DOI: 10.1007/978-3-030-66717-7_5.

29. Bécue, A., Maia, E., Feeken, L., Borchers, P., & Praça, I. A New Concept of Digital Twin Supporting Optimization and Resilience of Factories of the Future. *Applied Sciences*, 2020, vol. 10, article no. 4482. DOI: 10.3390/app10134482.

30. Værbak, M., Billanes, J. D., Jørgensen, B. N., & Ma, Z. A Digital Twin Framework for Simulating Distributed Energy Resources in Distribution Grids. *Energies*, 2024, vol. 17, article no. 2503. DOI: 10.3390/en17112503.

Received 27.05.2024, Accepted 20.08.2024

ІМІТАЦІЙНЕ МОДЕЛЮВАННЯ ВИРОБНИЦТВА ТА ЛОГІСТИКИ БЕТОННИХ ЗАВОДІВ

М. С. Бугаєвський, Ю. А. Петренко

Досліджується багатокритеріальне завдання підтримки прийняття рішень для ефективного управління виробництвом готової бетонної суміші та плануванням її доставки до будівельних майданчиків з урахуванням факторів ризику. Розроблення імітаційної моделі мережі виробничих потужностей та ланцюга збуту готових бетонних сумішей є ключовим елементом проєкту створення цифрового двійника у виробництві та логістиці бетонного заводу. **Актуальність** дослідження пов’язана з тим, що відновлення знищеного житлового фонду, відбудова пошкодженої інфраструктури та промислових будівель, відновлення робіт на всіх будівельних майданчиках країни призведе до різкого зростання попиту на бетон, що вочевидь буде перевищувати існуючі виробничі потужності. Тому, одним з ключових пріоритетів українських бетонних заводів вже сьогодні має стати реалізація стратегії та відповідних проєктів розвитку, що спрямовані на підвищення продуктивності без втрати якості. **Метою** дослідження є створення імітаційної моделі виробництва та доставки готового бетону у мережі заводів-виробників та будівельних майданчиків, у складі проєкту створення цифрового двійника для прийняття ефективних рішень управління ризиками в режимі реального часу для раннього виявлення неоптимальної діяльності у виробництві товарної бетонної суміші та логістиці. **Завдання**: провести аналіз проблем та особливостей створення цифрових двійників у виробництві та логістиці бетонних заводів; розробити імітаційну модель аналізу процесів виробництва та логістики готових бетонних сумішей; навести ілюстрований приклад моделювання процесів виробництва та логістики у мережі бетонних заводів та будівельних майданчиків.; провести оптимізаційні експерименти щодо визначення режимів функціонування системи. Отримані наступні **результати**. Розроблено імітаційну модель аналізу процесів

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

виробництва та логістики готових бетонних сумішей, за допомогою якої можливе вирішення цілого ряду завдань, серед яких оцінка раціональності та ефективності організації виробництва та доставки товарного бетону, визначення вузьких місць виробничих та логістичних процесів, прогнозування показників діяльності бетонних заводів, з урахуванням зміни умов виробництва, формування даних для прийняття рішень щодо скорочення часу простою заводу та клієнта тощо. **Висновки**. Наукова новизна дослідження пов'язана з вирішенням актуальної проблеми підготовки та планування логістичних дій щодо доставки товарного бетону в мережі заводів та будівельних майданчиків, шляхом створення комплексу оптимізаційних та імітаційної моделей, що сприяє ефективності прийняття рішень щодо управління ризиками для раннього виявлення неоптимальної діяльності у виробництві товарної бетонної суміші та логістиці. Ефективність запропонованого підходу проілюстрована на прикладі доставки бетону в мережі бетонних заводів Харківської області.

Ключові слова: товарний бетон; доставка бетону; ланцюг поставок; імітаційне моделювання; агентне моделювання; транспортування.

Бугаєвський Михайло Сергійович – аспірант каф. автоматизації та комп'ютерно-інтегрованих технологій, Харківський національний автомобільно-дорожній університет, Харків, Україна.

Петренко Юрій Антонович – д-р техн. наук, проф., проф. каф. автоматизації та комп'ютерно-інтегрованих технологій, Харківський національний автомобільно-дорожній університет, Харків, Україна.

Mikhailo Buhaievskyi – PhD Student of the Department of Automation and Computer-Integrated Technologies, Kharkiv National Automobile and Highway University, Kharkiv, Ukraine,
e-mail: bugaevsky73@gmail.com, ORCID: 0000-0002-9844-3146.

Yuri Petrenko – Doctor of Technical Sciences, Professor, Professor at the Department of Automation and Computer-Integrated Technologies, Kharkiv National Automobile and Highway University, Kharkiv, Ukraine,
e-mail: petrenko.yuriy.an@gmail.com, ORCID: 0000-0002-4596-8870.