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

UDC 004.94

doi: 10.32620/reks.2025.2.17

Mykhailo BUHAIEVSKYI, Yuri PETRENKO

Kharkiv National Automobile and Highway University, Kharkiv, Ukraine

PLANNING AND OPTIMIZATION MODELS IN READY-MADE CONCRETE PRODUCTION AND LOGISTICS

This study addresses *a multi-criteria decision support problem for the effective management of ready-mix concrete production and delivery planning. The research is conducted considering dynamic market demand, large-scale logistics challenges, and the need for production infrastructure development. The urgency of this work stems from the expected sharp increase in concrete demand due to the reconstruction of destroyed housing, infrastructure, and industrial facilities, in the context of the post-war reconstruction of Ukraine. This surge in demand is likely to exceed the current production capacity of Ukrainian concrete plants. Therefore, these enterprises' strategic priority is to enhance productivity while maintaining product quality.* ***This study aims*** *to develop a comprehensive framework of optimization and simulation models to support decision-making across a network of concrete plants and construction sites.* ***The main objectives*** *of this study are as follows: (1) to create a systematic representation of logistics processes in concrete production and distribution; (2) to develop a planning and optimization model for the ready-mix concrete supply chain; (3) to design an infrastructure optimization model for the production and distribution network; (4) to build a simulation model for analyzing production and logistics processes; and (5) to perform experiments to evaluate different system operation modes.* ***As a result****, several optimization models have been developed. These include a supply chain planning model, a sales network development model, and a coordination model for managing decisions across multiple plants. Additionally, a simulation model was designed to analyze the production and logistics processes. This model can be used to evaluate the efficiency of production and delivery strategies, identify bottlenecks, forecast plant performance under changing conditions, and support decisions to reduce downtime for both plants and customers.* ***Conclusions.*** *The scientific novelty of this research lies in the development of an integrated framework of optimization and simulation models that support production and logistics planning under uncertainty. These models account for production constraints, stochastic demand, variable delivery routes, mix composition, and time limitations. The framework also integrates economic indicators into a dynamic model, enabling real-time assessment of the impact of cost structures, raw material and transport expenses, and other parameters on overall enterprise profitability.*

Keywords: *ready-mixed concrete; concrete delivery; supply chain; production and logistics planning; optimization model; simulation modeling; agent modeling; transportation.*

1. Introduction

The restoration of destroyed housing stock, the 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 demand for concrete, which will obviously exceed existing production capacities [1]. Suppliers of ready-mix concrete mixtures are one of the significant participants in the construction project, and logistics pose significant challenges in the ready-mix concrete industry. Therefore, one of the key priorities of today's Ukrainian concrete plants should be the implementation of a strategy and relevant development projects aimed at increasing productivity without losing quality. A feature of ensuring concrete supplies is a short logistical lever and sensitivity to concrete mix delivery schedules [2]. In Ukraine, there are more than 300 concrete producers with a total capacity of about 12 million cubic meters per year. The base comprises six Kyiv producers with a total capacity of 7 million cubic meters per year. Other companies are small local producers operating in local markets. The specifics of the products (the need to locate the plant within 50-70 km from the place of consumption) determine the priority of regional (local) competition. The expected demand for concrete for the recovery period is 21-22 million cubic meters/year; thus, the need for additional capacity is 9-10 million cubic meters/year [3].

The activities of ready-mixed concrete producers should aim to increase the productivity of their concrete plants in order to provide the construction market with high quality standards and save money and time in the production and logistics system [4]. The larger the company, the more plants it has, the greater the volume of products produced and, accordingly and the higher the operating costs and pressure on logistics [5]. The work of concrete plants is strongly influenced by the stochastic nature of the processes of concrete production and delivery [6]. Making high-quality management decisions that determine the strategy and tactics of the functioning and development of concrete plants is possible only in the presence of a flexible optimization system that takes into account multi-parametricity and multi-criteria. Also, it provides automation of the process of finding the best parameters of the planning and management object to be automated.

The timely delivery of concrete by truck mixers to construction sites contributes not only to contractors' continuous and productive work but also to the cost-effective use of limited truck mixer resources on the part of the plant [7].

Thus, it is necessary to consider the non-stationarity of the process flow at enterprises in this area, which is caused by various factors [8]. Among these factors, one can single out uneven demand, changing requirements for the product range to meet customer needs, decentralization and distribution, since trucks and production sites can belong to several owners, large-scale logistics, since a large number of trucks carry out cyclical transportation, transport risks, etc.

In addition, ready-mix concrete production enterprises should be classified as developing systems; therefore, they have two components: operated and created (new stationary concrete plants, mobile concrete plants, reconstruction or modernization of capacities). In this case, we mean optimizing the development process in the form of expanding the network of plants, and not only the activities of operated facilities.

The solution to this problem is multi-optional in nature and depends on many conditions and restrictions. In this regard, during the design, planning, and management of the activities of the ready-mix concrete manufacturer, it is necessary to consider a complex of interrelated optimization tasks must be considered.

1.2. State of the Art and problem statement

The concrete delivery problem is an optimization problem that investigates the operation of concrete delivery vehicles, satisfying some time, demand, and resource availability constraints.

Research on the problems of allocating limited resources and optimizing freight flows began with two classic combinatorial optimization problems – the traveling salesman problem (TSP) and the vehicle routing problem (VRP) [9].

TSP does not make sense for our problem because concrete mixers do not perform movements between customers. VRP is a well-known integer programming problem that belongs to the NP-hard problem class, for which it is usually sufficient to find approximate solutions [10].

Typically, in real optimization problems, there are many additional constraints and variations. The most important and relevant for our problem are as follows: Capacitated VRP (CVRP) – each vehicle has a limited carrying capacity; VRP with Time Windows (VRPTW) – each customer must be served in a certain "time window"; Multiple Depot VRP (MDVRP) – several depots are used to serve customers; Split Delivery VRP (SDVRP) – each customer can be served simultaneously by several vehicles.

Since it is important to effectively satisfy customer requirements and adhere to their specified time windows for the successful implementation of construction projects in the transportation of ready-mix concrete, it can be considered as a problem of routing vehicles with limited capacity with time windows (CVRPTW), modified by the characteristics of other VRPs, such as split delivery constraints and taking into account multiple trips [11].

Adequate mathematical models of optimal transportation planning tasks can be the corresponding linear and dynamic programming tasks [12, 13] of the transport type, for the solution of which there are universal methods in a satisfactory time, primarily the simplex method and other options that take into account the specifics of tasks of this type (various complicated and modified).

However, in NP-hard tasks, it is difficult to obtain an optimal solution within a reasonable execution time for problems with a large number of elements when using exact solution methods; therefore, methods that make it possible to obtain approximate solutions are more often relied on. For this purpose, various methods and optimization software can be used, for example, CPLEX Optimizer IBM ILOG and others.

The procedure can be additionally limited depending on the set of operational and functional requirements, and this can be implemented in the form of various greedy algorithms [14].

Heuristic algorithms [15] are also popular, the purpose of which is to find an "almost optimal" solution within a reasonable period of time and include: genetic algorithms, ant colonies, etc. A mathematical model based on the ant colony algorithm for building ready-mix concrete delivery routes is considered in [16]. However, researchers often focus on considering only transport system factors, such as vehicle distance, load, and speed [17, 18].

A model of environmental fuel consumption for trucks when distributing concrete using an improved genetic algorithm was proposed in [19].

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

In [20], an integration of machine learning methods and genetic algorithms for optimizing concrete mixtures was performed. An improved reinforcement learning method for transporting ready-mix concrete, formulated as a Markov decision-making problem, is presented in [21].

Simulation modeling methods provide the highest quality results in the analysis of the dynamics of concrete production and distribution processes, which allow for a flexible, complete, and visual representation of the processes occurring in the system [22].

To date, three main approaches have been developed and are the most widely used: discrete-event modeling, system dynamics modeling, and agent modeling. Most studies related to concrete delivery modeling use the tools of discrete-event simulation modeling.

Decentralized multi-agent systems and simulation modeling [23] can be used to solve similar dynamic planning problems. In [24], the authors used the multi-agent approach as the basis for decentralized coordination associated with ant-based coordination mechanisms.

The influence of different dispatching policies on the concrete delivery process based on a discrete-event simulation model is considered in [25]. A discrete-event approach to the simulation modeling of concrete production and transportation processes has also been proposed [26]. However, the comparative results of the Arena simulation with real data are too artificial.

1.3. Objectives and methodology

Therefore, despite the achievements in the study of the problem under consideration, research that comprehensively considers the technological processes of production and logistics of ready-mix concrete mixtures is still lacking.

Thus, this study aims to create a complex optimization and simulation model for the production and delivery of ready-mix concrete in a network of manufacturing plants and construction sites for making effective decisions. In accordance with the stated goal of the study, it is necessary to reach the following objectives:

1. Formation of a systematic logistical presentation of enterprises' management processes for the production and distribution of ready-mix concrete.

2. Development of a planning and optimization model for the logistics supply chain of ready-mix concrete.

3. Development of a model for optimizing the production and distribution network infrastructure.

4. Development of a simulation model for the analysis of the processes of production and logistics of ready-mix concrete.

5. Experiments to determine the operating modes of the system.

The study employed a multi-stage methodological approach combining systems analysis, optimization methods, and simulation modeling to achieve the stated objectives. The research process was structured as follows:

1. Stage of system analysis. A comprehensive analysis of the ready-mix concrete production and distribution process was carried out. Key actors, material flows, constraints, and performance indicators were identified. This enabled the formulation of a systematic logistical representation of the enterprise management process.

2. The optimization modeling stage. Based on the system analysis, several mathematical models were developed to address various logistics planning and infrastructure optimization problems. Mixed-integer linear programming is used.

3. The simulation modeling stage. An agent-based simulation model was constructed to study the dynamic behavior of the production and logistics system under different scenarios. The model enables system performance evaluation in terms of efficiency, bottlenecks, resource utilization, and response to stochastic demand. In contrast to centralized optimization, the proposed approach integrates optimization logic into the behavior rules of agents within the simulation model.

4. Stages of experimentation and validation. Simulation experiments were conducted to evaluate different operating modes of the system, test the robustness of planning decisions, and assess the potential impact of infrastructure changes. The models were implemented using AnyLogic and validated using empirical or estimated operational data.

This structured methodology allowed for a comprehensive and coherent study of the problem, integrating both strategic and operational aspects of production and logistics management for ready-mix concrete.

According to the proposed methodology, this paper has the following structure. Section 2 presents a systematic logistic representation of the management processes of ready-mix concrete production and distribution enterprises. Section 3 describes a planning and optimization model in the ready-mix concrete logistics supply chain. Section 4 presents a model for optimizing the production and distribution network infrastructure. Section 5 discusses the issues of creating a simulation model for the analysis of ready-mix concrete production and logistics processes. Section 6 presents an example of the modeling of the production and logistics processes of ready-mix concrete. Section 7 discusses the obtained results and details the modeling experiments.

Section 8 summarizes the key contributions and outlines potential directions for future research.

2. Systematic logistic representation of management processes of ready-mix concrete production and distribution enterprises

The management of enterprises engaged in the production and supply of ready-mixed concrete requires the integration of strategic, tactical, and operational decision-making levels. This includes planning production capacities, developing sales networks, and optimizing logistics processes. A systematic logistics view allows you to model these interconnected processes, ensuring effective resource management and meeting customer demand.

The main components of a systematic view are as follows:

- demand forecasting and sales planning: assessing the potential market capacity in each area and determining planned sales volumes, considering the pricing function;
- production capacity management: analyzing the current productivity of concrete plants and the possibilities of increasing it through modernization, considering costs and expected productivity gains;
- delivery logistics optimization: planning concrete truck routes considering restrictions on the number of vehicles, delivery time windows, etc.

When modeling concrete logistics, we will take into account:

- orders;
- resources (concrete plants, concrete trucks);
- business rules and restrictions (who provides whom, quantitative quotas of carriers and suppliers, delivery time, calendar, etc.)
- costs (tariffs, fines and sanctions, etc.)

The enterprise may have its own fleet of vehicles for concrete transport. If the existing fleet of vehicles is insufficient to meet the demand of all its consumers, the enterprise may use the services of a third-party carrier company by renting special vehicles from it. Since concrete is ordered in large quantities, it is natural that the volume of each customer's order is expected to exceed the volume of the smallest capacity concrete truck.

The goals of the enterprise are as follows:

- satisfy the daily orders of all its customers at lower costs (minimization of the total cost of transportation);
- to optimize vehicle use.

Concrete producers usually have a regional distribution (Fig. 1). A region is an area that includes a set of customers (construction sites), a set of vehicles (concrete mixers) owned or from the carrier's motor transport company (MTC), and one concrete plant.

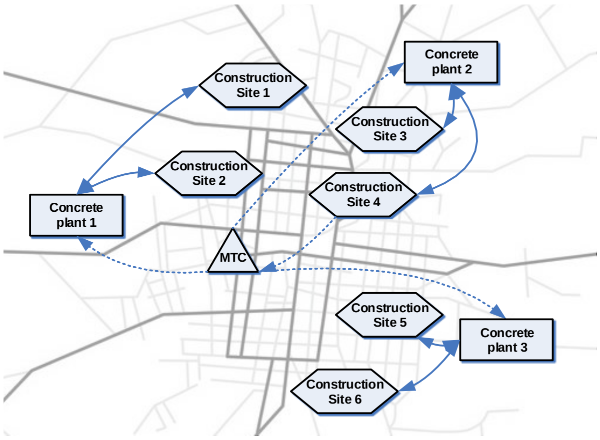

Fig. 1. Example of regional representation for a concrete plant network and a sales network

Systematic logistic representation of the management processes of ready-mix concrete production and distribution enterprises provides the basis for the development of optimization and simulation models that take into account the relationships between demand, production capacities and logistical constraints. The integration of modern digital technologies such as the Internet of Things and Digital Twins [27] contributes to increasing the efficiency and adaptability of such systems, which is critically important in a dynamic market and increasing requirements for the quality and timeliness of concrete delivery.

3. Planning and optimization model in the ready-mix concrete logistics supply chain

A key role in managing flow processes in the ready-mix concrete supply chain is played by issues of optimization planning of concrete supplies and sales based on demand forecasting, the impact of pricing decisions / placement prices by supply areas, and plan-fact analysis.

The goal of optimization planning is to maximize the difference between total revenues and costs for concrete distribution.

Assume that customers in the area can be served only by a concrete plant tied to this particular area. Vehicles can be either their own or belong to the concrete plant. External from the carrier, a certain MTC. Each vehicle can be used in any area. It starts its movement from the MTC or the plant to which it is assigned and must return there after visiting the last customer.

Some constraints that will be used in the model are as follows:

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

- one product (with further expansion of the model to consider multiple types of ready-mixed concrete);

- each concrete mixer must leave the MTC empty for loading to the concrete plant for loading;

- each vehicle must leave the loaded plant and return empty to the plant or to its MTC;

- each vehicle visits only one customer at a time.

Possible vehicle movement options:

1. Initial movement from MTC to the concrete plant. This is the first movement of a concrete mixer with an empty container from the MTC (to which it belongs) to the concrete plant to serve construction sites (which are connected to it).

2. A round trip between the plant and the construction site. This is a certain number of travel cycles between the plant and construction sites.

3. Movement from one plant to another through a construction site visit. Thus, the vehicle leaves the area and never returns.

4. The final movement from the construction site to the MTC. The final empty movement from the last serviced construction site to the MTC to which the vehicle is assigned.

Here, we present a mathematical model of the distribution of concrete between the routes of vehicles from the MTC that deliver them to the construction sites in the service areas.

Let us define:

- R – multiple regions (a region is one concrete batching plant and its associated customers);

- I_r – multiple customers in the region $r \in R$;

- V – all vehicles involved (both belonging to an MTC and taken from external sources);

- $V_{own} \subseteq V$ – own vehicles;

- $V_{ext} \subseteq V$ – vehicles taken from external sources (other MTC);

- A_v – the MTC that the vehicle belongs to v;

- N_v – N_v – number of concrete mixers available at the MTC;

- d_i – demand for concrete of the i^{th} customer, m³;

- Q_v – vehicle v's capacity, m³;

- c_{vij} – cost of servicing a vehicle trip v from the plant j to the customer i;

- c_{v0j} – cost of moving an empty concrete mixer v from the MTC to the plant j;

- c_{vi0} – cost of moving an empty concrete mixer v from the last customer i back to the MTC;

- p_i – concrete sales price to the client per unit volume, UAH/m³;

- t_v – total operating time (moving, loading, delivery, return) of the vehicle v during the day;

- t_{ij} – estimated delivery time of concrete to the customer i from the plant j;

- T_i – maximum allowable time for the first delivery to the customer i;

- Pn_i – fine for each violation of the delivery deadline to the customer i;

- T^{max} – maximum permitted duration of vehicle operation per day;

- M – a large number, much larger than the number of routes between the MTC, concrete plants and customers.

Variables:

- $x_{vij} \in \{0,1\}$ – if the vehicle v visiting customer i from the plant j;

- $y_{vi} \in \{0,1\}$ – if the vehicle v does initial route from the MTC to the factory j;

- $y_{vr} \in \{0,1\}$ – if the vehicle v moves into the area r;

- $z_v \in \{0,1\}$ – if the vehicle v leaves its MTC (i.e. it is active);

- $z_{vi} \in \{0,1\}$ – if the vehicle v returns empty from the customer i back to the MTC;

- $s_{vi} \in \{0,1\}$ – if the vehicle v delayed the first delivery to the customer i.

Limitations:

1. A vehicle can leave the MTC no more than once (i.e. either it is used in the route or it is not, in which case it must leave the MTC):

$$\sum_{r \in R} y_{vr} \le z_v,\ z_v \le 1,\ \forall v \in V. \quad (1)$$

2. A vehicle can visit a region no more than once:

$$y_{vr} \le 1,\ \forall v \in V, r \in R. \quad (2)$$

3. Meeting the demand of every customer:

$$\sum_{v \in V} Q_v \cdot x_{vij} \ge d_i,\ \forall i \in I_r, \forall r \in R. \quad (3)$$

4. If the vehicle serves at least one customer from a plant j, it must take the following initial route from the MTC to that factory:

$$\sum_{i \in I, r \in R} x_{vij} \ge y_{vi},\ \forall v \in V, \forall j \in R. \quad (4)$$

5. If the vehicle has finished delivery to the customer i, it may be returned to the MTC:

$$z_{vi} \geq \frac{1}{M}\sum_{j\in R} x_{vij},\ \forall v \in V, i \in I_r. \qquad (5)$$

6. Link between visiting the area and serving customers in the area (if the vehicle serves at least one customer from the area):

$$\sum_{j\in R, i\in I_r} x_{vjj} \leq M\cdot y_{vr},\ \forall v \in V, \forall r. \qquad (6)$$

7. Ensuring exit from the area after the visit (if the vehicle has visited the area, it must then either return to the MTC (empty from the last customer), or move to another area because of the customer):

$$y_{vr} \leq \sum_{i\in I_r} z_{vi} + \sum_{r'\neq r} y_{vr'}\ \ \forall v \in V, \forall r. \qquad (7)$$

8. Limitation of the number of available concrete trucks at the MTC:

$$\sum_{j\in R} y_{vj} \leq N_v,\ \forall v \in V_{ext}. \qquad (8)$$

9. Taking into account the penalty for delay in the first delivery:

$$s_{vi} \geq (t_{ij} - T_i)/M,\ \forall v \in V, i \in I_r. \qquad (9)$$

10. Maximum duration of vehicle operation per day:

$$t_v \leq T^{max},\ \forall v \in V. \qquad (10)$$

Transportation per route is only considered for one customer because each x_{vij} defines every single route.

The payback period for revenues and expenses may be different (for example, income from the sale of concrete is received later than transportation costs). To reflect this in the optimization, we introduce weight coefficients: $\alpha > 0$ – weighting factor for income; $\beta > 0$ – weighting factor for expenses.

That is, if revenues have less weight due to the risk of late payments, we can put $\alpha < 1$. Or if the costs are more important (because they are spent immediately), then β we can put more.

The objective function maximizes the difference between income and expenses.

$$\max\left(\alpha\cdot\sum_{v\in V}\sum_{i\in I_r, j\in R} p_i\cdot Q_v\cdot x_{vij} - \beta\cdot\sum_{v\in V}\left(\sum_{i\in I_r, j\in R} c_{vij}\cdot x_{vij} + \sum_{j\in R} c_{v0j}\cdot y_{vj} + \sum_{i\in I_r, j\in R} c_{vi0}\cdot z_{vi} + \sum_{i\in I_r, j\in R} Pn_i\cdot s_{vi}\right)\right). \qquad (11)$$

Thus, it is a weighting of revenues and expenses in the objective function using coefficients that reflect the time value of money or differences in payback priorities.

4. Models for optimizing the production and distribution network infrastructure

Next, we consider the model considering the development of the sales network.

Let us define:

- S_r – forecast of potential sales in the area r, m³;
- P_r – planned sales volume in the area r, m³;
- $\pi_r(P_r)$ – function of the average concrete price in the area r as a function of sales volume P_r;
- E_r – basic productivity of a concrete batching plant in the area r during the period, m³/period;
- ΔE_r – increase in plant productivity in the area r in case of modernization, m³;
- c_r^{pr} – costs for implementing a plant development project in the area r, thousands UAH;
- B^{pr} – budget restrictions for the implementation of plant development projects in the areas, thousands of UAH.

Variable:

- $k_r \in \{0,1\}$ – binary variable: $k_r = 1$ – if a modernization project in the area r is implemented within the planned period, $k_r = 0$ – otherwise.

Main limitations:

1. Possible sales limitations (planned sales volume cannot exceed the potential capacity of the area):

$$0 \leq P_r \leq S_r,\ \forall r. \qquad (12)$$

2. Plant capacity limitations (you cannot sell more than the plant capacity allows, even taking modernization into account):

$$P_r \leq E_r + \Delta E_r\cdot k_r,\ \forall r. \qquad (13)$$

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

3. Resource limitations for modernization project implementation (cannot exceed the development budget):

$$\sum_{j\in R} c_j^{pr}\cdot k_j \le B^{pr}. \qquad (14)$$

The objective function is to maximize the revenue minus the investment costs for modernization:

$$\max\left(\sum_r\left(\pi_r(P_r)\cdot P_r\right)-\sum_r\left(c_r^{pr}\cdot k_r\right)\right). \qquad (15)$$

Let's build a coordination model for making decisions about the network of factories in the area (previously we assumed that one factory serves the area). This model allows us to determine from which factory and in what volume to satisfy the demand of a specific order, optimizing costs and considering resource and logistics constraints.

Let us define:

- J – multiple concrete plants in the area;
- g_j – available amount of raw materials at the plant j, which can be used for additional production;
- θ – raw material consumption rate for the production of a unit of concrete (by components - cement, sand, crushed stone, additives, water);
- p_j – plant capacity j (maximum daily production volume);
- c_j – cost of a unit of concrete from the factory j (including production cost);
- F_j – fixed costs for launching / upgrading /activating additional production at the plant j;
- t_{dj} – estimated concrete production time d_i for the customer i from the raw materials available at the factory j.

Variables:

- $h_{ij}\in\{0,d_i\}$ – planned delivery volume of a customer order i from the factory j;
- $l_j\in\{0,1\}$ – if additional concrete production is being activated at the factory j;
- $u_j\in\{0,1\}$ – if the customer's order is fully satisfied.

Limitations:

1. Meeting demand:

$$\sum_{j\in J} h_{ij}\ge d_i\cdot u_i,\ \forall i\in I_r. \qquad (16)$$

2. Supply restrictions from each factory:

$$\sum_{i\in I_r} h_{ij}\cdot\theta\le g_j\cdot u_i,\ \forall j\in J. \qquad (17)$$

3. Limitation of plant capacity per day:

$$\sum_{i\in I_r} h_{ij}\le p_j,\ \forall j\in J. \qquad (18)$$

4. The delivery time should not exceed the allowable period:

$$h_{ij}>0\Rightarrow t_{ij}+t_{dj}\le T_i,\ \forall i\in I_r, j\in J. \qquad (19)$$

Minimize total costs (transportation, raw materials, modernization):

$$\min\left(\sum_{i\in I_r}\sum_{j\in J} h_{ij}\cdot(c_j+c_{ij})+\sum_r\left(l_j\cdot F_j\right)\right). \qquad (20)$$

A generalized procedure for assessing investment costs for the modernization of production capacities should take into account both the technical condition of the existing assets and the strategic goals of the enterprise. In the future, we plan to structure this as a multi-step modular assessment based on the following parameters for individual technological units: age (as a percentage of their normative service life), condition (according to technical audit data: satisfactory, worn, critical), energy efficiency, and modernization potential. As a result, we obtain a matrix of plant characteristics, which can then be integrated into the modernization cost function formulation.

Thus, we have considered a set of optimization models that describe the dynamics of the characteristics of concrete production and delivery links, considering the influence of scenario conditions, constraints, and various control parameters.

The presented optimization models form the basis for determining the objective functions and constraints on the behavior of agents in the logistics network simulation model for the supply of ready-mixed concrete. Each agent in our model acts according to local rules formed on the basis of the corresponding parts of the optimization model.

Such a model allows us to abandon the use of centralized mathematical optimization methods (integer programming or evolutionary algorithms), since the optimal or approximately optimal solution is achieved in the process of interaction of agents that respond to environmental constraints, demand and available resources. Thus, simulation modeling with built-in logic based on optimization models becomes a tool for solving distribution, planning, and coordination problems in dynamic logistics environments.

In contrast to centralized optimization, the proposed approach integrates optimization logic into the behavior rules of agents within the simulation model. This agent-based mechanism allows the system to dynamically adjust to changes in demand, available transport units, or production constraints, ensuring flexibility and adaptability in decision-making.

Although the optimization is not performed in a traditional centralized manner, the following ensures computational efficiency and accuracy:

- local optimization rules derived from the objective function structure and constraints of the original models;
- dynamic adaptation of agents to environment states, allowing near-optimal solutions to be achieved in typical operational scenarios;

scalability of the approach, because the simulation runtime grows linearly with the number of agents, whereas the decision-making complexity per agent remains constant or bounded.

5. Simulation model for the analysis of ready-mixed concrete production and logistics processes

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

The simulation model is developed in the AnyLogic environment and consists of components, each of which reflects a separate element of the dynamics of the enterprise's behavior and concrete distribution infrastructure.

Figure 2 shows the structure of the agent simulation model. The following are implemented in the developed simulation model using the class of active objects (agents), the following are implemented: concrete plant (ConcretePlant); order (Order); construction site (ConstructionSite); truck mixer (TruckMixer); supplier of raw materials (Supplier); order for raw materials (MaterialOrder); truck transporting raw materials (Vehicle). Thus, we have a population in the required number of all types of agents. Each agent has its own variables and a mathematical model that describes its behavior based on the provisions considered in this work.

In work [28], we described the technical and operational model of concrete production and delivery.

The initial technical and operational model of concrete production and delivery has now been expanded to the management and economic levels, including key revenue and cost parameters. This allowed us to take into account not only supply logistics but also the economic efficiency of the enterprise, particularly through indicators such as sales revenue, transportation costs, costs of modernization, and use of raw materials. At this stage, these parameters are integrated into the behavior of the relevant agents in the simulation model.

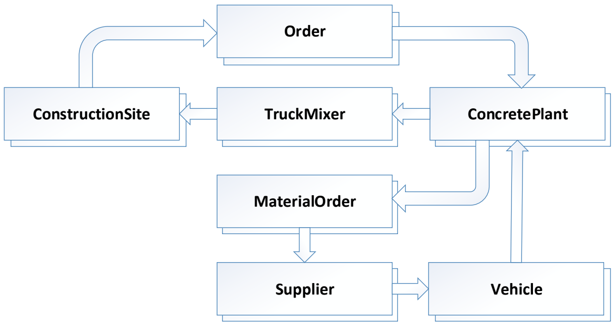

Fig. 2. An agent simulation model structure for analyzing concrete production and logistics processes

ConcretePlant agents make decisions on production volumes, production costs, considering raw material and resource costs, current productivity, and possible modernization. They assess the feasibility of expanding production based on available budget, raw material volumes, transportation costs, and expected revenue.

For this, the ConcretePlant agent has the following parameters:

- production price (ProductionCostPerCubicMeter), which considers the following into account: raw materials, electricity, and equipment depreciation;
- basic price (CostPerCubicMeter): separately by concrete type;
- factory expenses (dailyFixedCost), which takes the following into account: security, personnel, energy costs, rent;
- the cost of maintaining the plant’s fleet (idleTruckCostPerHour), which allows the model to show the economic inefficiency of large downtime, helps to find "bottlenecks" and stimulates schedule/route optimization;
- cost of truck rental for transportation (idleRentalTruckCostPerHour).

Results that the ConcretePlant agent accumulates: total revenue from all orders; average revenue per m³; net profit, as the difference between revenue and costs.

ConstructionSite agents, customers, initiate a demand for concrete (Order) with specified time and volume constraints, which affects the profitability of individual supply chains.

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

These agents receive the following management and economic level parameters:

- penalty for delay in the first delivery (penaltyPerHourDelay), which is an incentive for other agents to adhere to the schedule;
- the cost of order cancelation (orderCancelCost) if the concrete is spoiled or the customer refuses to pay;
- a priority surcharge (prioritySurcharge), which is an additional fee if the delivery must be made in a narrow time window or before the standard deadline;
- remote delivery surcharge (remoteDeliverySurcharge), when delivering over long distances exceeding a given threshold.
- minimum order revenue (minimumOrderRevenue), introduced to make it economically sensible to deliver small batches;
- waiting fee at the site (waitingFeePerHour).

TruckMixer agents select the route and supplier considering transportation costs and order fulfillment times.

TruckMixer agents receive the following management and economic level parameters:

- fuel cost (fuelCostPerKm);
- average fuel consumption (fuelConsumptionPerKm);
- driver cost (driverCostPerHour);
- maintenance cost per 1000 km (maintenanceCostPer1000km);
- depreciation cost per trip (depreciationPerTrip).

The overall calculation of economic efficiency is modeled by accumulating revenue from completed orders and total costs associated with production, logistics, and modernization. Thus, the model allows the assessment of the economic consequences of management decisions made in conditions of limited resources and variable demand, providing a practical basis for supporting strategic and operational planning.

6. Example of modeling of ready-mix concrete production and logistics processes

In our example, the model simulates concrete delivery to the Kharkiv region. The supply chain includes three production 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 mixer trucks, 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 with different or the same volumes. When the production department receives an order from a construction site, it checks for the presence of residues from the current orders. If the required quantity of the given type is available, the plant sends a loaded truck to the customer. Otherwise, the order waits in a line until the plant produces a sufficient quantity of the product.

Fig. 3 shows the model after startup. Agents operate in the space of the OpenStreetMap geographic information system. The names of the initial locations of production facilities and distributors are taken from the database. The search engine of the geographic information system is used to search for places on the map and place agents there, making it possible to flexibly form both a network of concrete plants and a distribution network of construction sites.

In Fig. 4 a screen with the results generated for a separate concrete plant is presented.

The infrastructure of the supply network, including the number and capacities of concrete plants and the number and types of concrete mixer trucks, is configured based on the results of the infrastructure optimization model before the simulation starts. This model determines the most efficient allocation of production resources and fleet sizes across facilities to minimize transportation costs and maximize service level.

In the case study, we experimented with different initial configurations of production capacities and truck fleets, as defined by the infrastructure optimization step. The simulation allows observing how the selected infrastructure performs under stochastic demand.

Once customer demand (i.e., construction site orders) is generated, the system assigns production tasks and delivery vehicles using local agent behavior rules. These rules are derived from the planning and optimization model described in Section 3, which aims to minimize delivery delays and ensure product freshness:

- each plant agent verifies the inventory and production capabilities based on constraints similar to those described in the optimization model;
- if a feasible delivery is possible, the assignment is made immediately – otherwise, the order is queued;
- route creation and truck dispatching rely on heuristics inspired by the objective function in the optimization model.

Trucks move along real roads, and routes are created when vehicles start moving in their directions. A histogram of the volume of concrete produced and a quantitative indicator of free trucks can be seen near each concrete plant. Near the construction site, the quantitative value of concrete delivered for the entire time and icons of trucks waiting to be unloaded are visible. By clicking on production and construction objects, you can switch to viewing the simulation results.

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

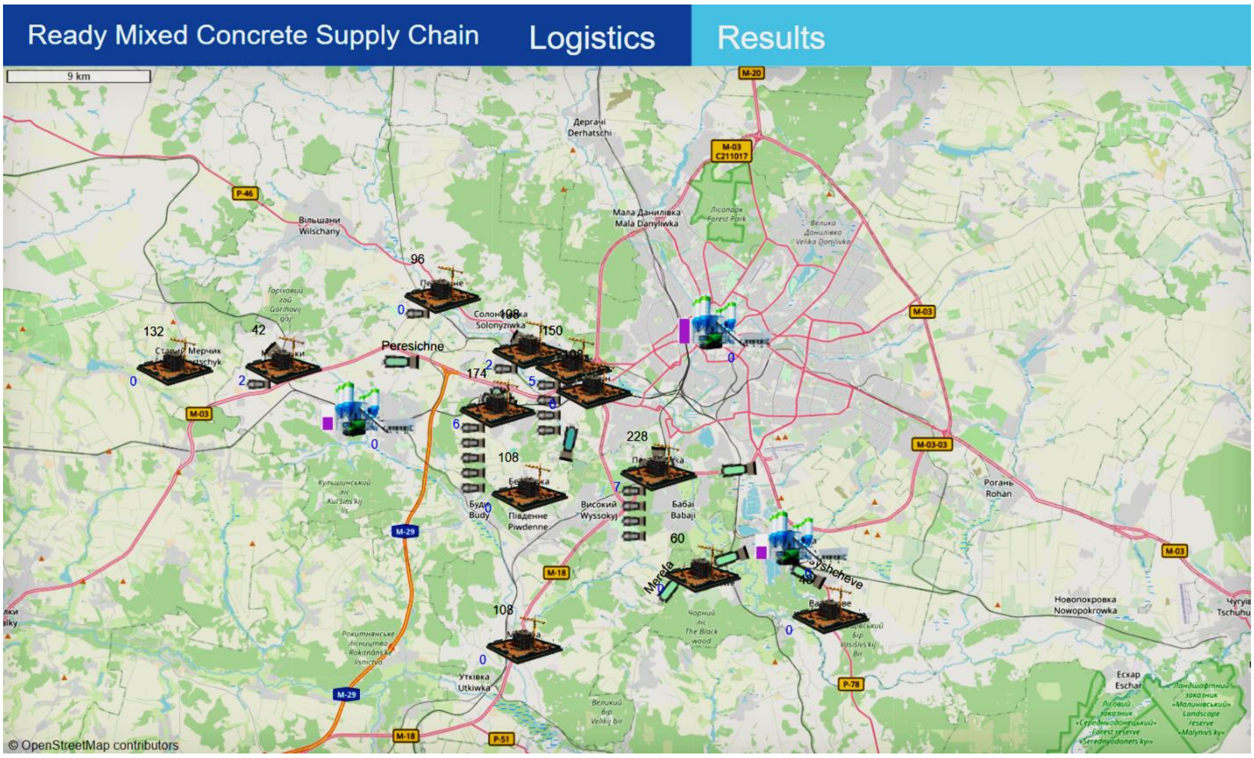

Fig. 3. Monitoring concrete delivery logistics when a simulation model is run

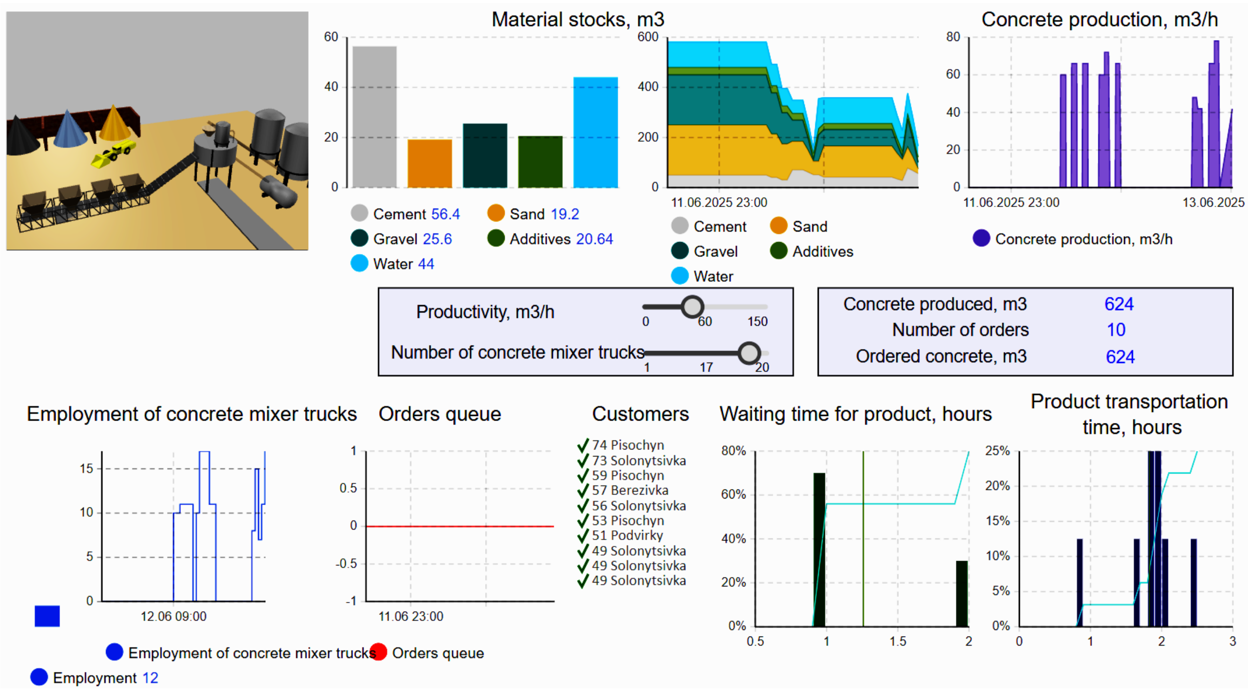

Fig. 4. Simulation results for the ConcretePlant agent

supply, concrete production in quantitative terms and in the dynamics of production/shipment, the occupancy 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), histograms of the distribution of product waiting time and transportation time. 3D animation of a concrete shipment from the plant is shown.

As the simulation progresses, agents react dynamically to the current environment. When delays accumulate or when demand grows beyond initial capacity, the system "re-optimizes" through agent

Radioelectronic and Computer Systems, 2025, no. 2(114)
ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

behavior adjustments (reallocating trucks, delaying low-priority deliveries etc.). This reflects the ideas of simulation-based optimization introduced in Section 5. Furthermore:

- each truck tracks its travel time, delivery delays, and wait time at construction sites, allowing the evaluation of current planning decisions;
- production agents adapt batch production to meet emerging demand profiles;
- in the background, the environment monitors aggregate KPIs, which can be used to fine-tune the initial infrastructure parameters.

Fig. 5 presents data on the routes of concrete mixer trucks, where all time parameters are recorded, making it possible to use this data in the future when forming delivery schedules.

7. Discussion

Experiments were conducted to test and verify the developed simulation model. Various graphs are formed, including linear graphs of costs, and profit by days (Fig. 6).

To evaluate the results, we present calculated data for determining the profit of a concrete plant per month (Table 1).

1. Monthly income:

Profit = sold m³ × cost = 300 m³/day × 30 days × 1 400 UAH = 12 600 000 UAH.

2. Production costs:

Production costs = 300 × 30 × 800 = 7 200 000 UAH.

3. Shipping costs (per 1 m³)

Shipping costs = 15 km × 2.5 UAH = 37.5 UAH/m³

Shipping costs per month = 300 m³ × 30 days × 37.5 UAH = 337 500 UAH.

4. Fuel and maintenance costs:

Fuel and maintenance costs = 50 routes/day × 30 days × (250 + 15 × 6 × 1.5) UAH = 1 125 000 UAH.

5. Drivers' salaries:

Drivers' salaries = 50 routes with a duration of 1.5 h = 75 h × 150 × 30 = 337 500 UAH.

6. Fixed factory costs:

Fixed factory costs = 10 000 UAH × 30 = 300 000 UAH.

Thus, the monthly expenses are 9 300 000 UAH.

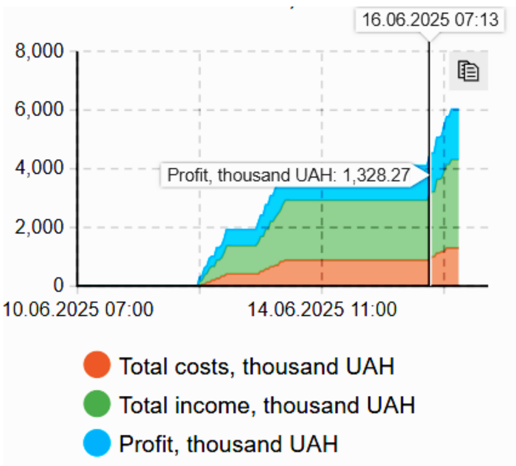

Fig. 6. Costs, income, and profit in thousands of UAH

Table 1

Economic parameters of the production and logistics system of the enterprise

Parameter	Value
Expenses	
Production cost of 1 m³, UAH/m³	800
Delivery cost per 1 km per 1 m³, UAH/km/m³	2.5
Fuel costs for 1 route, UAH	250
Hourly payment to the truck driver, UAH/hour	150
Truck maintenance per 1 km, UAH/km	1.5
Daily fixed costs of the factory, UAH	10 000
Profits	
Selling price 1 m³, UAH/m³	1 400
Average delivery distance, km	15
Average delivery volume, m³	6
Daily production volume, m³	300

Concrete mixer truck routes

Destination point	Start of waiting loading	Start of delivery	Start of waiting unloading	Start of return to the factory	Travel time to the construction site	Travel time to the plant
Staryi Merchyk	85.29	101.21	101.44	0.0	0.23	0.11
Korotych	84.89	100.43	100.62	0.0	0.19	0.11
Korotych	83.3	100.47	100.67	0.0	0.19	0.11
Korotych	101.06	0.0	0.0	0.0	0.19	0.2
Korotych	83.91	100.84	101.03	0.0	0.19	0.11
Korotych	85.34	100.34	100.54	101.29	0.19	0.11
Manchenky	100.81	102.58	0.0	0.0	0.19	0.2
Korotych	84.03	100.65	100.85	0.0	0.19	0.18
Manchenky	86.34	0.0	0.0	0.0	0.23	0.23
Staryi Merchyk	84.51	0.0	0.0	0.0	0.18	0.18
Staryi Merchyk	85.99	0.0	0.0	0.0	0.23	0.23
Staryi Merchyk	83.21	101.48	0.0	0.0	0.11	0.11
Staryi Merchyk	84.93	0.0	0.0	0.0	0.23	0.23
Staryi Merchyk	102.57	0.0	0.0	0.0	0.23	0.23
Staryi Merchyk	84.7	101.23	101.46	102.58	0.23	0.11

Fig. 5. Routes of the plant's concrete mixer trucks and their time parameters

The monthly profit is 3 300 000 UAH. with intensive daily production (300 m^3/day), which is realistic for an average stationary plant. This fully coincides with the results obtained during the modeling process.

These results match the simulated output and demonstrate the economic feasibility of operating at this production scale. The optimization models contributed to minimizing transportation costs (337 500 UAH/month) and balancing fleet use (50 routes/day), ensuring a realistic and cost-effective distribution strategy.

The profit ratio between the customer price and the productivity of the "last mile" logistics is defined as the profit curve of the finished mixture. It illustrates the compromise between the material margin, a price indicator (UAH/m^3), standardized by subtracting the cost of raw materials from the product price, and the productivity of the last mile logistics (m^3/h). The characteristic curve represents the point locus necessary to achieve profit for a certain period. Such a graph has a deep economic and logistical meaning and is a good analytical tool. It is a graph where on the X axis is the productivity of logistics (m^3/h), on the Y axis is the margin (UAH/m^3).

This graph illustrates the trade-off: higher margins are usually possible with lower volumes (fewer customers nearby), and higher productivity is possible with customers closer, but at a lower cost. Here, we can see the optimum – the point where the profit is greatest.

We have also added contour lines of equal profit (10, 15 and 20 thousand/h) – they will be hyperbolic.

Figure 7 shows an example of a productivity curve obtained during the simulation for one of the plants.

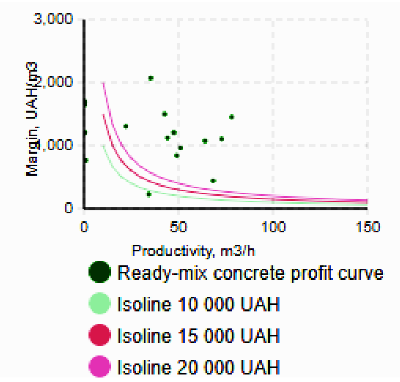

Fig. 7. Profitability curve for one of the plants

By analyzing the graph, it can be noted that there is no obvious linear relationship. However, there are scenarios with high margins and high productivity, which give maximum profit. There are points (orders) with low productivity and high margin, and vice versa. This is a typical sign that it is necessary to improve logistics or optimize queues. Others, with high productivity but low margin, give moderate profit. Isolines clearly show the profit thresholds. Our points (orders) are mainly located above the isolines, indicating profitability. The higher the point on the graph (with the same productivity), the greater the margin. The integration of optimization models of agent behavior, economic parameters, and analytical tools into a concrete production and delivery enterprise model has significantly increased its applied value and analytical depth. Thanks to the optimization of agent decisions (regarding the distribution of orders and logistics), the model allows simulation of realistic interactions between system participants under conditions of limited resources and variable demand.

The introduction of economic parameters (cost, delivery costs, salaries, depreciation, etc.) made it possible not only to take into account the financial aspects of the activity but also to calculate key indicators of economic efficiency. Additional analytical tools, in particular the profitability curve of the ready-mix concrete mix, made it possible to visualize the trade-offs between margin and productivity of the “last mile” to identify areas of efficient work and potential losses. Thus, the model was transformed from a simple simulation of the production process into a strategic tool for supporting management decisions, capable of assessing the impact of changes in market or operating conditions on the economic feasibility of the ready-mix concrete manufacturer.

The presented simulation-based approach demonstrated the applicability of agent-based modeling for the planning and optimization of concrete delivery in a regional construction supply chain. In comparison to traditional static routing or linear programming models, our framework introduces dynamic behavior, geographic realism, and emergent properties in the delivery process.

Unlike most existing models that assume fixed infrastructure and pre-planned schedules, our approach combines infrastructure optimization with agent-based decision-making under uncertainty. The integration with real geographic data and use of dynamic demand generation at multiple sites allows the adaptability of logistics systems to be evaluated in near-real-world scenarios.

In some studies, the distribution of ready-mixed concrete is solely considered a classical vehicle routing problem [12, 22]. In contrast, our work presents a digital twin that encompasses the entire production and logistics system, from concrete batching plants to the construction site distribution infrastructure.

Many existing approaches [11, 16] rely on rigid, discrete-event models limited to a fixed number of production and consumption nodes. While such models can be useful for analytical analysis, their applicability to real-world, dynamic environments is restricted, particularly in large-scale or variable systems.

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

The proposed system is scalable and configurable, allowing adaptation to different configurations of production and distribution networks. The dynamic adaptation of agents to changes in demand, resource availability, and production constraints, which reflects realistic decision-making conditions in logistics operations, is a key advantage.

Another significant distinction of our model is the integration of a geographic information system that incorporates actual transportation infrastructure. This enables precise travel times estimation for concrete mixer trucks, unlike most existing studies that rely on abstract networks or pre-defined distance matrices.

Moreover, unlike approaches [10, 15], in which optimization problem formulations fail to capture the complexity of real-world concrete production and delivery or overlook critical practical constraints, our method does not rely on centralized optimization techniques such as integer programming or evolutionary algorithms. Instead, near-optimal behavior emerges through agent interactions that respond to environmental constraints, demand fluctuations, and available resources.

The proposed method allows decision-makers to test various configurations of production capacities and fleet sizes before implementation. The visibility into truck utilization, line times, and delivery delays supports better operational planning and resource allocation. In particular, the ability to observe how infrastructure constraints affect delivery performance is critical for large-scale infrastructure planning under volatile demand.

We recognize several limitations of this study. First, the current model focuses on a single product type, with plans to expand to include multiple concrete types. Second, although routing is based on real maps, it currently does not incorporate real-time traffic data, which may affect delivery timing. Third, while the model captures operational-level dynamics, it assumes that production capacity can be increased without raw material constraints – an assumption that may not hold in all real-world scenarios.

8. Conclusions

Thus, a study of the multi-criteria decision support task for the effective management of ready-mix concrete production and planning its delivery to construction sites was conducted. The tasks were implemented within the research framework, which allowed the creation of a comprehensive model of decision support and process management in the production and logistics of ready-mix concrete.

1. The system-based logistic representation of management processes made it possible to cover all key elements of the functioning of the concrete production and delivery enterprise, which formed the basis for building a complex optimization and simulation models.

2. The planning and optimization model in the logistics chain made it possible to consider factors of demand, delivery routes, time constraints, and production capacities, which increased the validity of management decisions. The optimization model allows a fairly complete consideration of possible options for moving vehicles in concrete logistics.

3. Optimization of the production and distribution network infrastructure made it possible to identify configurations that provide the best ratio between operating costs, transport, and profitability under variable system operation and modernization and development project implementation scenarios.

4. The simulation model of production and logistics processes allowed the reconstruction of real processes, considering the developed optimization models, stochastic factors, dynamic changes in demand, and resource constraints, which made it possible to test various strategies for managing the production and logistics system of the enterprise.

5. Analysis of the modeling results showed a high dependence of profitability on the interaction of margin and productivity, which was visualized using analytics tools, particularly profitability graphs. This allows not only to assess current efficiency but also to see different scenarios and predict the consequences of changes in system parameters. The use of the proposed models led to a reduction in average delivery delay by 18% and an increase in fleet utilization efficiency by approximately 13% compared to baseline configurations without optimization. In addition, the number of unfulfilled orders was reduced by up to 30% in high-demand scenarios.

In general, the combination of optimization, economic approaches, and multi-agent simulation modeling allowed us to create an adaptive and practically oriented decision support system in the field of ready-mix concrete production and logistics.

Although the case study is based on a Ukrainian regional context, the proposed models are applicable to various types of decentralized logistics systems, such as cement or asphalt, involving batch production and time-sensitive delivery.

Future research will be aimed at modeling possible failures and breakdowns of technological equipment and concrete mixers in order to find the optimal supply/transportation cost balance in these conditions and prevent production plan disruption or production capacity underutilization.

Contribution of authors: optimization model of planning in the logistics supply chain of ready-mix

concrete, models of optimization of the infrastructure of the production and distribution network, simulation model of analysis of production processes and logistics of concrete plants, analysis of modeling results and manuscript – **Mikhailo Buhaievskyi**; analysis of problems and features of decision-making and management in the production and logistics of concrete plants, models of optimization of the infrastructure of the production and distribution network – **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

This research was conducted without financial support.

Data availability

The manuscript contains no associated data.

Use of artificial intelligence

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

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

References

1. *Rynok tsementu ta betonu Ukrayiny: 2023 ta prohnoz potreb* [Cement and concrete market of Ukraine: 2023 and demand forecast] Available at: https://readymix.pro/rinok-cementu-ta-betonu-ukrayini-2023-ta-prognoz-potreb. (accessed 15.04.2025).

2. 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.

3. *Strukturni zminy ta vyklyky v budivel'niy industriyi Ukrayiny: analiz ta prohnozy* [Structural changes and challenges in the construction industry of Ukraine: analysis and forecasts] Available at: https://kse.ua/wp-content/uploads/2024/09/02_09_24_Zvit_Strukturni_zmini_ta_vikliki_v_budivelnii--_industrii--.pdf (accessed 15.04.2025).

4. 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.

5. Optimization of dispatching schedule of ready mixed concrete (RMC) plant for multi-plant and multi-site operation condition: a literature review. *International Journal of Emerging Technologies and Innovative Research*, 2021, vol. 8, iss. 5, pp. f783-f789. Available: http://www.jetir.org/papers/JETIR2105770.pdf. (accessed 15.04.2025).

6. 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.

7. Gaikwad, K., & Thakare, S. B. Optimization of Ready Mix Concrete (RMC) Dispatching Schedule: A Literature Review. *International Journal of Engineering Development and Research*, 2019, vol. 7, iss 1, pp. 327-332. Available: https://rjwave.org/IJEDR/papers/IJEDR1901060.pdf. (accessed 15.04.2025).

8. 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.

9. Kralev, V., Kraleva, R. Combining Genetic Algorithm with Local Search Method in Solving Optimization Problems. *Electronics*, 2024, vol. 13, article no. 4126. DOI: 10.3390/electronics13204126.

10. Schmid, V., Doerner, K. F., Hartl, R. F., & Salazar-González, J.-J. Hybridization of very large neighborhood search for ready-mixed concrete delivery problems. *Computers & Operations Research*, 2010, vol. 37, pp. 559–574. DOI: 10.1016/j.cor.2008.07.010.

11. Dönmez, O. A., & Öner, E. Optimizing ready-mixed concrete transportation by a truck mixer routing model for concrete plants. *Journal of Engineering Sciences and Design*, 2024, vol. 12, iss. 4, pp. 802-820. DOI: 10.21923/jesd.1445781.

12. 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.

13. Sarkar, D., Gohel, J., & Dabasia, K. Optimization of ready mixed concrete delivery for commercial batching plants of Ahmedabad, India. *International Journal of Construction Management*, 2021, vol. 21, no. 10, pp. 1024-1043. DOI: 10.1080/15623599.2019.1602582.

14. Hsie, M., Huang, C. Y., Hsiao, W. T., Wu, M. Y., & Liu, Y.C. Optimization on Ready-Mixed Concrete Dispatching Problem via Sliding Time Window Searching. *KSCE J Civ Eng*, 2022, vol. 26, pp. 3173–3187. DOI: 10.1007/s12205-022-1273-0.

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

15. Douaioui K., Benmoussa O., & Ahlaqqach M. Optimizing Supply Chain Efficiency Using Innovative Goal Programming and Advanced Metaheuristic Techniques. *Applied Sciences*, 2024, vol. 14, no. 16, article no. 7151. DOI: 10.3390/app14167151.

16. Choi, J., Xuelei, J., & Jeong, W. Optimizing the Construction Job Site Vehicle Scheduling Problem. *Sustainability*, 2018, vol. 10, iss. 5, article no. 1381. DOI: 10.3390/su10051381.

17. Rong, H., Wenbo, C., Bin, Q., Ning, G., & Fenghong, X. Learning Ant Colony Algorithm for Green Multi-depot Vehicle Routing Problem. *Journal of System Simulation*, 2021, vol. 33, iss. 9, article no. 2095. DOI: 10.16182/j.issn1004731x.joss.20-0349.

18. Zhang, Z., Qu, T., Zhao, K., Zhang, K., Zhang, Y., Liu, L., Wang, J., & Huang, G. Q. Optimization Model and Strategy for Dynamic Material Distribution Scheduling Based on Digital Twin: A Step towards Sustainable Manufacturing. *Sustainability*, 2023, vol. 15, iss. 23, article no. 16539. DOI: 10.3390/su152316539.

19. 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, iss. 16, article no. 9256. DOI: 10.3390/app13169256.

20. 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.

21. Chen, Z., Wang, H., Wang, B., Yang, L., Song, C., Zhang, X., Lin, F., & Cheng, J. C. Scheduling optimization of electric ready mixed concrete vehicles using an improved model-based reinforcement learning. *Automation in Construction*, 2024, vol. 160, article no. 105308. DOI: 10.1016/j.autcon.2024.105308.

22. Galić, M., & Kraus, I. Simulation Model for Scenario Optimization of the Ready-Mix Concrete Delivery Problem. Selected Scientific Papers. *Journal of Civil Engineering*, 2016, vol. 11, pp. 7-18. DOI: 10.1515/sspjce-2016-0014.

23. Matejević-Nikolić, B., & Živković, L. Development of the Simulation Model for Ready Mixed Concrete Supply Chain Cost Structure. *Tehnički vjesnik*, 2023, vol. 30, no. 1, pp. 102-113. DOI: 10.17559/TV-20220310120002.

24. 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, iss. 19, article no. 4124. DOI: 10.3390/math11194124.

25. Weiszer, M., Fedorko, G., Molnár, V., Tučková, Z., & Poliak, M. Dispatching policy evaluation for transport of ready mixed concrete. *Open Engineering*, 2020, vol. 10, no. 1, pp. 120-128. DOI: 10.1515/eng-2020-0030.

26. Jamal, J., Hasan, M., Azad, A., Ahmad, M., & Ahmmed, M. Optimization of Ready-Mix Concrete Operations: A Comprehensive Approach Through Practical and Simulation-Oriented Data. In *7th IEOM Bangladesh International Conference on Industrial Engineering and Operations Management*, Dhaka, Bangladesh, 2024, pp. 230-240. DOI: 10.46254/BA07.20240036.

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

28. Buhaievskyi, M., & Petrenko, Y. Simulation of production and logistics for concrete plants. *Radioelectronic and Computer Systems*, 2024, vol. 2024, no. 3. pp 190-204. DOI: 10.32620/reks.2024.3.13.

Received 12.02.2025, Accepted 20.05.2025

МОДЕЛІ ПЛАНУВАННЯ ТА ОПТИМІЗАЦІЇ У ВИРОБНИЦТВІ ТА ЛОГІСТИЦІ ГОТОВОГО БЕТОНУ

М. С. Бугаєвський, Ю. А. Петренко

Досліджується багатокритеріальне завдання підтримки прийняття рішень для ефективного управління виробництвом готового бетону та плануванням його доставки до будівельних майданчиків в умовах динаміки ринкових вимог, масштабної логістики, обмежень та розвитку виробничої системи тощо. **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 комплексу оптимізаційних та імітаційної моделей виробництва та доставки готового бетону у мережі заводів-виробників та будівельних майданчиків для прийняття ефективних рішень. **Завдання**: формування системного логістичного подання процесів управління підприємствами з виробництва та розподілення готового бетону; розробка моделі планування та оптимізації в логістичному ланцюгу постачання готового бетону; розробка моделі оптимізації інфраструктури виробничої та розподільчої мережі; розробка імітаційної моделі аналізу процесів виробництва та логістики готового бетону; проведення експериментів щодо визначення режимів функціонування системи. Отримані наступні **результати**. Розроблено комплекс оптимізаційних моделей: модель планування в логістичному ланцюгу постачання готового бетону, модель з урахуванням розвитку збутової мережі, модель координації для ухвалення рішення щодо мережі заводів у регіоні. Розроблено імітаційну модель аналізу процесів 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 виробничих та логістичних дій в мережі бетонних заводів та їх клієнтів, шляхом створення комплексу оптимізаційних та імітаційної моделей, які враховують виробничу, транспортну й економічну підсистеми підприємства, враховують стохастичний попит, змінні маршрути доставки, рецептуру суміші та часові обмеження виробництва, а також інтегрують економічні показники у динамічну модель, що дозволяє оцінювати вплив структури витрат, вартості сировини, транспортних витрат та інших параметрів на загальний прибуток підприємства в режимі реального часу.

Ключові слова: готовий бетон; доставка бетону; ланцюг поставок; планування виробництва та логістики; оптимізаційна модель; імітаційне моделювання; агент; транспортування.

Бугаєвський Михайло Сергійович – асп. 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.

Mykhailo 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.