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Development of the Simulation Model for Ready Mixed Concrete Supply Chain Cost Structure

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Abstract: Supply of Ready Mixed Concrete (RMC) is a common process of concrete works on any structure. There is often a need to supply one or more construction sites simultaneously from multiple concrete plants. This paper presents a new simulation model of RMC supply and delivery from three concrete plants to three construction sites. The model is dynamic, easily managed, and adjustable and it allows proper estimation of the cost and time required to solve the problem of RMC supply. Model verification was performed using a case study of concrete supply to construction sites in the city of Niš, Serbia. The case study is based on real parameters obtained from specific concrete plants and construction sites. The results of the simulation experiment with varying number of mixers indicate that there is a significant influence of vehicle number and volume on idling costs. Based on the model analysis in the case study, scenario 10 (minimum total idling cost is 14,09 €) is recommended as the optimal combination of truck mixers for the considered case study. The simulation results indicate that the selection of an adequate combination can significantly reduce the costs of idling, for both the mixer and the pump, which leads to minimal idling time and, consequently, to timely pouring of concrete without reducing its quality.

Keywords: cost; optimization; ready mixed concrete; simulation modeling; supply chain

1 INTRODUCTION

Of all artificial materials, concrete is the most widely used throughout the world. Ready mixed concrete (RMC) is a basic construction material used in the construction of most structures. As many as 60-70% of all modern structures were built using RMC [1]. Owing to its properties and strict quality requirements, the process of concrete production, delivery, and pouring is of interest both for contractors and concrete suppliers [2]. With the increasingly demanding requirements for concrete quality and with continuous development of new concrete types, concrete is usually produced in completely controlled conditions and environment, thus making concrete production a highly competitive business on the market. Because of the limited shelf life of fresh concrete mass, concrete plants can only serve construction sites up to a certain distance. This constraint limits the number of potential clients and increases competition among concrete plants operating in overlapping areas [3]. Considering that material costs are relatively similar, concrete plants achieve improved economy through lower prices of concrete transportation, concrete pouring services (if they rent pumps), penalty fees incurred by stoppage and prolonged pump and mixer idling at the construction site, as well as through offering a reliable service in order to remain competitive on the market. RMC is made to order and customized according to the client's requirements, while its delivery needs to account for the construction site constraints as well as technological constraints (concrete cannot be prepared in advance and then stored). Fresh concrete is delivered to a construction site using truck mixers, whereby it is necessary to preserve its quality throughout. Regardless, cement begins to set within several hours, even after the addition of retarders. Therefore, concrete may remain in the mixer drum for a limited time before its installing quality deteriorates or before it fully sets, which can damage the mixer drum and lead to disproportionate maintenance costs. Likewise, it is not recommended for truck mixers to transport concrete in a partially loaded drum or to deliver the same batch of concrete partially to one site and then to the next one on the route without reloading, because it might lead to increased setting rate [4]. In addition, concrete should be installed continuously to avoid joints, which can reduce the hardness and quality of the constructed elements.

Since there is limited time to deliver RMC, timeliness and flexibility need to be considered when coordinating concrete delivery to different construction sites. From a business perspective, concrete plants strive towards the highest possible production and delivery volume as fast as possible, whereas construction sites require continuous supply without mixer pile-ups that will necessarily lead to queues. Therefore, an efficient and well-balanced concrete delivery schedule will not only increase productivity but also reduce costs, and it is one of the key contributory factors for successful work execution. This poses a challenge to decision makers in concrete plants, who have to coordinate the processes of concrete production, transportation, and pouring. Most concrete plants are based on automated concrete production, which allows the concrete with requested properties to be produced in a fairly short period. However, the process of transportation planning still heavily relies on skills and experience, much less so on scientific methods and models. It is thus necessary to develop a model that will attempt to optimize RMC transportation from a concrete plant to construction sites. The problem becomes more complicated when multiple construction sites are in demand of simultaneous delivery, both timely and cost-effective, from one or more concrete plants. In such cases, in order to ensure continuity of work and the required quality with lower costs, concrete production and delivery need to be planned meticulously. The issue is a complex one and warrants research across several fields: logistics, chain supply, and just-in-time production. Different parameters and pieces of information need to be considered, for instance, plant-to-site distance, total required amount of concrete, traffic conditions, construction site conditions, number of available mixers and their capacity, etc. RMC total cost usually comprises the cost of materials, production, delivery, pouring, and additional costs incurred by poor planning. Considering that material costs are more or less fixed, the goal should be to optimize transportation and avoid penalty costs for mixer or pump idling. Simultaneous RMC supply to one or more construction sites from multiple concrete plants is a process that requires careful planning in order to minimize the cost. Since the process involves risk and specific degrees of probability, optimal parameters cannot be determined using any of the deterministic mathematical methods. This paper presents a new model for solving the problem of simultaneous RMC supply to multiple construction sites from multiple concrete plants in a stochastic environment. AnyLogic© software was used to develop an algorithm that enables planning of RMC supply to a maximum of three construction sites from a maximum of three concrete plants. The model is able to determine the cost and duration of concrete works and to provide different analyses and variations of parameters to obtain a better solution. In this paper, the model is applied to determine the optimal number of mixers supplying construction sites from specific concrete plants for the purpose of achieving minimal total and unit costs. The model allows continuous work, reduction of lost time at construction sites, and efficient concrete delivery scheduling. The model is dynamic, easily managed, and adjustable, and it allows proper estimation of the cost and time required to solve the problem of RMC supply. Model verification was performed using a case study of concrete supply to construction sites in the city of Niš, Serbia. The case study is based on real parameters obtained from specific concrete plants and construction sites. Three concrete plants supplied three construction sites that were in need of the same type of concrete at the same time. The concrete plants possess their own truck mixer fleet as well as concrete mobile pump.

2 LITERATURE REVIEW

The transportation problem, extensively studied for years, ever since the emergence of operations research and linear programming during WW2, was used to solve the problem of transportation of products from different sources to different destinations, specifically to minimize transportation costs. Later, the vehicle routing problem (VRP), proposed by Dantzig [5], was used to optimize the route of identical vehicles from their starting point to their destination. With the development of various mathematical methods, new optimization methods for solving this problem also developed. The problem has also been recognized in different areas of civil engineering, and this literature review focuses on the RMC delivery problem (RMCDP) and the supply chain.

Over the past decade, there have been several attempts to model the RMCDP, which is a generalized VRP. The main differences between RMCDP and VRP can be summarized as follows: in the RMCDP, a vehicle can deliver concrete on any route to only one buyer and a vehicle can travel for a limited time because fresh concrete has a limited shelf life [6]. The said methods consider only the static nature of input parameters: optimal material transportation with minimization of transportation costs. However, the concrete as well as asphalt transportation problem [7] is dynamic by nature within a stochastic environment. The following lines focus on papers dealing with the problem of RMC supply and scheduling using different methods, techniques, and models.

Galić et al. [5] presented a simulation model structured in the Enterprise Dynamics simulation software, which is based on DES (discrete event simulation). They considered the problem of concrete transportation from four concrete plants to five construction sites in the city of Osijek, Croatia. According to a case study for three proposed scenarios (different routes), the authors determined the most favorable one in terms of transportation costs and duration. Another concept of simulation modeling, System Dynamics (SD), was used to develop a simulation model of the RMC supply process [8]. The authors' conclusions indicate that the information obtained using the simulation model can help achieve more economical RMC supply by maintaining the number of queuing truck mixers at a desired level. Kinable et al. [9] presented exact and heuristic algorithms for solving the concrete delivery problem. Exact approaches use the Mixer Integer Programming model and Constraint Programming model, while heuristics, first of all, rely on an efficient best-fit scheduling procedure, and second, utilize the Mixer Integer Programming model to improve delivery schedules locally. In a multi-objective programming model, Lin et al. [3] formulate the dispatching operations of ready mixed concrete (RMC) trucks as a job shop problem with recirculation, which includes time windows and demand postponement, as well as the external cost of transport. The study examines the differences between the optimal cost under volumetric regulation and under the weight regulation in determining RMC truck loads. Liu et al. [10] developed a time-space network model that optimizes operation costs (including production cost, trucks cost, pumps cost, and penalty costs). A heuristic algorithm was developed in which various types of priority rules were employed, and these rules consist of production scheduling and choosing mixers, trucks, and pumps. Yan et al. [11] proposed an integrated model, which is a combination of production planning of RMC and truck dispatching problems. Liu et al. [12] proposed a mixed-integer programming applying genetic algorithms (GA) in the model. They analyzed an RMC mixer, several construction sites, and a few trucks and pumps with various specifications in order to minimize the total cost, which consists of four parts: transportation cost, penalty cost of construction sites waiting for the first delivery, penalty cost of pumps waiting for the first truck delivery, and penalty cost of construction sites waiting for the next delivery. In [13], Talian developed a simulation model in Extend v4 to present the integrated process of production-transportation-consumption of fresh concrete using the data obtained from actual processes as model parameters. A model based on genetic algorithm presented by Feng and Wu [14] aims to obtain the optimal solution of a delivery problem. A simulation computer program called RMCSIM (Ready Mixed Concrete SIMulation) is presented in [15]. The model was developed to simulate concrete production and transport by truck mixers with two different capacities (5 m^3 and 7 m^3), which serve different locations located at variable distances from the concrete plant. It was shown that the combinations of truck mixers in the fleet with the two considered capacities do not have a significant effect on concreting service performance. Panas et al. [16] analyzed the process of concrete supply using simulation-based modeling so as to determine the concrete truck mixer fleet size that best meets the needs of the project. Concrete truck mixer fleet size is examined in terms of utilization and productivity criteria. Based on a previous study [17], which combined DES and GA, Lu and Lam [18] optimized one-plant-multisite RMC plant operations in Hong Kong. Simulation experiments are used to make a decision on the optimal number of truck mixers of each type to be dispatched to multiple construction sites on any particular day, with the purpose of minimizing total operational inefficiencies with limited resource availability. In another study [19], Lu and Lam developed a special-purpose simulation tool called HKCONSIM (Hong Kong CONcreteSIMulation) for rapidly building a simulation model for a typical one-plant-multisite system of concrete production and delivery based on a DES approach. Lu et al. [20] applied the particle swarm optimization (PSO) technique to optimize a concrete delivery simulation model, aimed at improving the total operational inefficiencies by minimizing non-productive time due to mixer idling caused by early or late arrival. The developed DES model in [21] attempts to improve the entire process of RMC delivery by simultaneously minimizing waiting time of truck mixers at the construction site and the site idling time. Comparison of simulation results showed that variable interval dispatching was better than constant interval dispatching. Schmid et al. [22] developed a method to solve a highly complex problem in logistics and combinatorial optimization, such as the concrete delivery problem, involving multiple plants, multiple construction sites, and a variety of trucks and pumps, which aimed to minimize the transportation cost. In this research, they proposed combinatorial algorithms: the combination of variable neighborhood search (VNS) and exact method. Sarkar et al. [23] developed a delivery schedule model that was written in MATLAB software. They used real time data for a commercial ready mixed concrete (RMC) plant in Ahmedabad city of Gujarat, India. Yan et al. [24] used network flow techniques to construct a systematic model that helps to effectively plan production and truck dispatching schedules under stochastic travel times. A case study was performed using real data from a Taiwan RMC concrete plant. One study [25] proposes a model for RMC supply scheduling in the event of temporary vehicle breakdown. Azambuja and Chen [26] described the implementation of failure mode, effects, and criticality analysis tool to assess supply chain risks, identify vulnerabilities, and measure the effect of disruptions of an RMC supply chain. Interviews with concrete batch plant managers and current demand, production, and delivery performance data served as the input for the analysis. Yan and Lai [27] developed a network flow model to decide on an optimal RMC supply schedule that also integrates overtime considerations. The model was formulated as a mixed integer network flow problem and evaluated using real operating data. Asbach et al. [4] solved a complex scheduling or vehicle routing problem. They scheduled the tours of concrete mixer vehicles over a working day from concrete-producing depots to concrete-demanding customers and vice versa. Maghrebi et al. [28] mathematically modeled the RMC dispatching problem using two approaches: integer programming (without time windows) and mixed-integer programming (with time windows). In another study, Maghrebi et al. [29] tested a robust genetic algorithm and column generation with various sizes of actual RMC problems. In paper [30], based on RFID application and multi-agent simulation, authors proposed an information tracking and supply mechanism for prefabricated supply chain.

Thus far, there have been numerous studies about RMC production and delivery problems. Proposed solutions for these problems involve a large number of algorithms, such as genetic algorithms [12, 14, 18, 29], heuristics, simulations [5, 13, 15, 16, 19], neural networks, fuzzy logic [31], etc. Unlike the previous studies, the present study applies a simulation based on the combination of DES and ABM methods, whereby a new model is developed that considers three concrete plants and three construction sites for simultaneous RMC supply via different truck mixer fleets.

3 DEVELOPMENT OF THE RMC SUPPLY CHAIN SIMULATION MODEL

Simulation modeling has proved to be a suitable method for efficient solving of complex real-world problems. It provides an important way of analysis which is easily verified, communicated and understood. Simulation software provides a dynamic environment for the analysis of computer models while they are running, including the possibility to view them in 2D or 3D [32]. Depending on the simulation project goals, the available data, and the nature of the system being modeled, different problems may call for different methods [32].

Owing to the characteristics of the RMC delivery process, a dynamic system in a stochastic environment, the Discrete Event Simulation (DES) method has also been shown as suitable for application. Changes within the system occur discontinuously, at specific moments in time. In order to represent the process as comprehensively as possible, to overcome the deficiencies of specific approaches, and to get the most out of each approach, it is possible to apply a hybrid method, as a combination of DES and Agent-based Modeling (ABM). In an agent-based model the system is described from the point of view of individual objects that may interact with each other and with the environment [33].

This paper presents a new simulation model of RMC delivery from three concrete plants to three construction sites. A discrete event model describes the process starting from the production of concrete in the concrete plant, through transport, to concrete pouring on construction sites, where the truck mixers then appear as agents.

3.1 Methodology and Model Description

Simulation is used as the decision-making tool, while the creation of the simulation model took considerable time, expertise, and attention. This section provides a detailed description and creation steps for the proposed model. The simulation model is developed in AnyLogic 8.7.8. simulation software using JAVA programming. It is designed to be used for planning, analysis, and optimization of the RMC delivery process for cases of simultaneous RMC supply from a maximum of three concrete plants to a maximum of three construction sites. The decision to develop a model with three plants and three sites was based on the authors' experience, as most standard construction jobs for residential buildings in urban areas do not require more than three plants and sites for simultaneous concrete work. The model can also be applied to cases where two sites are supplied from one concrete plant, one site from two concrete plants, or to any other combination. The following criterion is adopted for the model: continuous concrete delivery; minimum plant, truck mixers, and site idle time and minimum penalty costs; and maximum efficiency.

To create the process chart (Fig. 1), the RMC delivery process is first divided into several individual sub-processes:

- queueing of truck mixers in the concrete plant;
- preparing of fresh concrete in the concrete plant and loading into the truck mixer;
- departure to the construction site;
- queuing of truck mixers at the construction site;
- unloading of truck mixers at the construction site;
- return of truck mixers to the concrete plant.

Each of these sub-processes is represented by a corresponding block and enumerated according to the number of plants and sites, while agents in the model (truck mixers) allow the possibility of adding properties to the DES model.

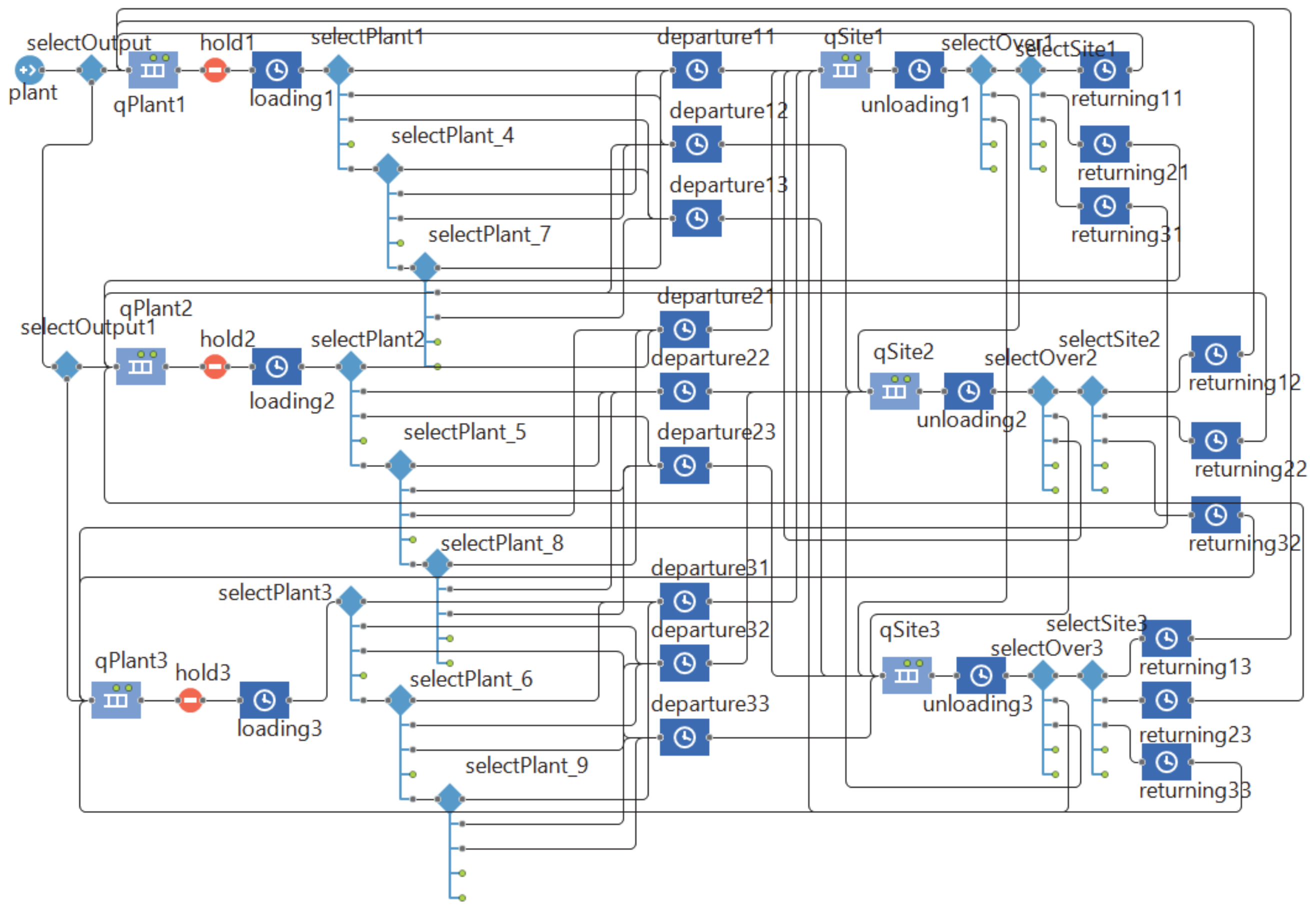

Figure 1 RMC supply chain process chart: from three concrete plants to three construction sites

Start is defined by the block *source* (plant), from which a defined number of truck mixers is generated. Their main properties are their affiliation with a specific concrete plant and the volumes of their drum, which is a variable property. Each concrete plant uses a specified number of truck mixers with various or same volumes, which will be defined as input before the simulation has been run. Before the concrete is loaded, a mixer queue is formed (block *qPlant*) in each plant, with FIFO (first-in-first-out) type priority. This rule ensures that the first truck mixer to arrive will also be the first to be loaded. After the truck mixer is loaded (block *loading*) it leaves the plant and goes (block *departure*) to a specified construction site (through block *selectPlant*). The rule for selecting the first site to receive the concrete delivery is defined first according to site priority (site 1 with high priority, then site 2, etc.), and then according to minimum construction site idle time and minimum truck mixer idle time. For example, if site 2 has no truck mixer in the queue, and site 1 and site 3 have at least one truck in their queues, the first ready truck mixer will go to site 2. When a truck mixer arrives to a site, it joins the queue (block *qSite*) with FIFO type priority. This rule ensures that the first truck mixer to arrive will also be the first to be unloaded. After the truck mixer is unloaded (block *unloading*), it leaves the site and returns (block *returning*) to its affiliated plant (through block *selectSite*). During the simulation, the amounts of produced concrete in specific plants as well as the amounts of concrete delivered to specific sites are summed. When the resulting sum is equal to a site's demand or to the capacities of a specific plant, the given site/plant halts production/delivery. The simulation ends when every site has been supplied with the demanded amounts of concrete.

3.2 Description of the Model Input and Output Data (Parameters)

Owing to the stochastic nature of the RMC delivery process (e.g., uncertainty during the activity, traffic conditions, etc.), the durations of specific parts of the process, being random variables, are represented by their probability distributions. Based on the authors' experience from previous studies and on the experience of experts from concrete plants and construction sites, the expression in Eq. (1) is used to calculate loading time.

$$time_{load} = \frac{Volume_{truck\_mixer}}{{}_{plant}\,Production\ Rate}, \qquad (1)$$

where:
$time_{load}$ - duration of loading truck mixer / h,
$Volume_{truck\_mixer}$ - quantity of fresh concrete in the truck mixer drum / m^3,
${}_{plant}Production\ Rate$ - quantity of fresh concrete made by plant, triangular distribution with parameters (0,9; 1,0; 1,1) is used /m^3/h.

Similarly, expression Eq. (2) is used to calculate unloading time.

$$time_{unload} = \frac{Volume_{truck\_mixer}}{{}_{pump}\,Production\ Rate} \qquad (2)$$

where:
$time_{unload}$ - duration of unloading truck mixer / h,
$Volume_{truck\_mixer}$ - quantity of fresh concrete in the truck mixer drum / m^3,
${}_{pump}Production\ Rate$ - pump efficiency, triangular distribution with parameters (0,8; 1,0; 1,2) is used, / m^3/h.

The time required for transportation from specific plants to specific sites is calculated using Eq. (3).

$$time_{transport} = \frac{Distance_{plant-site}}{Function\_transport}, \qquad (3)$$

where:
$time_{transport}$ - truck mixer traveling time / h,
$Distance_{plant\text{-}site}$ - distance from plant to site / km,
$Function\_transport$ - transportation speed, dynamic parameter of average speed represented by distribution function β-eta (4-parameter) with parameters (1,546; 1,574; 14,828; 24,101), based on the research conducted in [34, 35], where the same urban area was considered.

The following input data (Fig. 2) are fed into the simulation before running it: plant production rate (m^3/h); pump production rate (m^3/h); supply quantity (m^3); site demand (m^3); distance from each plant to each site (km); costs: transportation (€/m^3) dependent on distance, cost of concrete production (€/m^3), and pouring (€/m^3), idling pump (€/h), idling truck mixer (€/h). Additionally, before input data feeding, it is necessary to define the fleet size and truck mixer volume in a separate excel file, which is an integral part of the model.

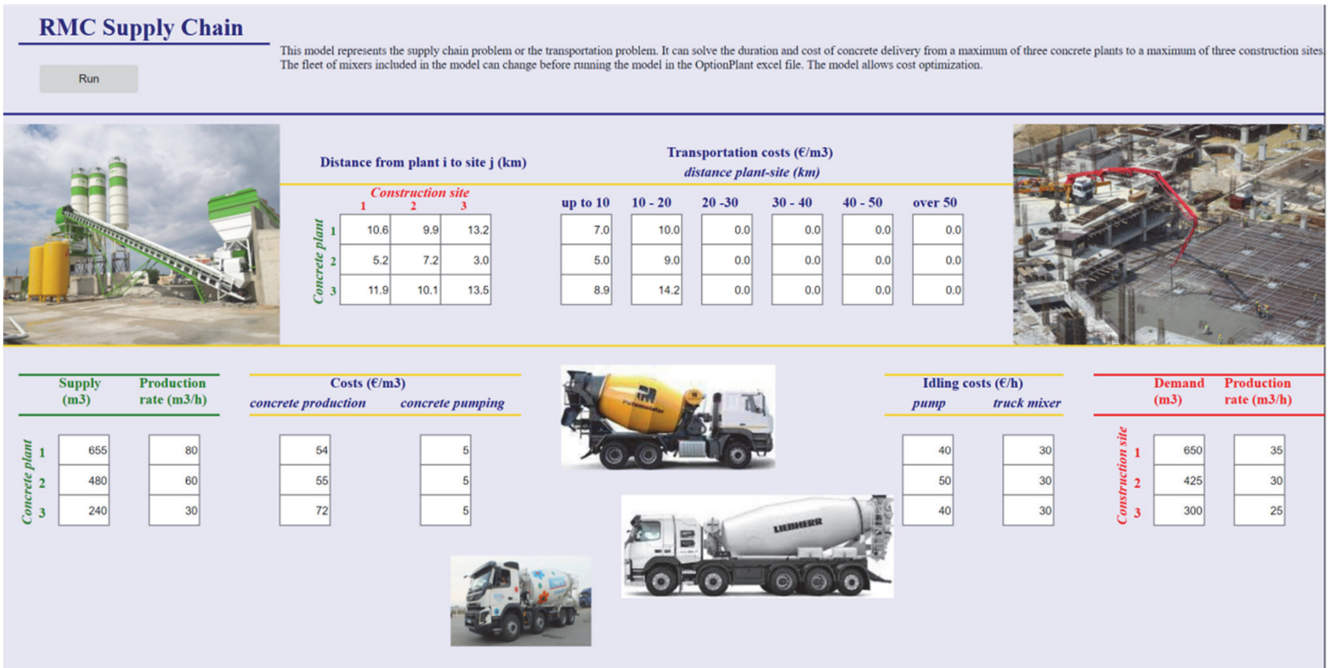

Figure 2 RMC supply chain process simulation model: input parameters

The total cost of the process in the model is calculated based on the input unit costs and Eq. (4) (n is the number of concrete plants and m is the number of construction sites), while the total penalty cost follows Eq. (5).

$$Total\ cost = \sum_{i=1}^{n}\sum_{j=1}^{m}\begin{pmatrix} Production\ cost_i + Transport\ cost_{ij} + \\ + Penalty\ cost_j + Pouring\ cost_j \end{pmatrix}, \qquad (4)$$

where:
$Total\ cost$ - total cost of concreting / €,
$Production\ cost_i$ - cost of concrete production in plant i / €,
$Transport\ cost_{ij}$ - cost of concrete transport from plant i to site j / €,
$Penality\ cost_j$ - cost of idling (truck mixer and pump) at site j / €,
$Pouring\ cost_j$ - cost of concreting with pump at site j / €,

$$Penalty\ cost = \sum_{j=1}^{m}\begin{pmatrix} Cost\ of\ truck\ mixer\ idling_j + \\ + Cost\ of\ pump\ idling_j \end{pmatrix}, \qquad (5)$$

According to concrete plant data, the costs of truck mixer and pump idling are not charged additionally if the idling does not exceed 45 minutes. Idling exceeding 45 minutes is charged according to applicable pricing rates for every initiated three-quarters of an hour interval.

During the simulation, the process can be displayed using various representations, such as parameters and variables, charts, graphs, 2D representations (Fig. 3), 3D representations, etc.

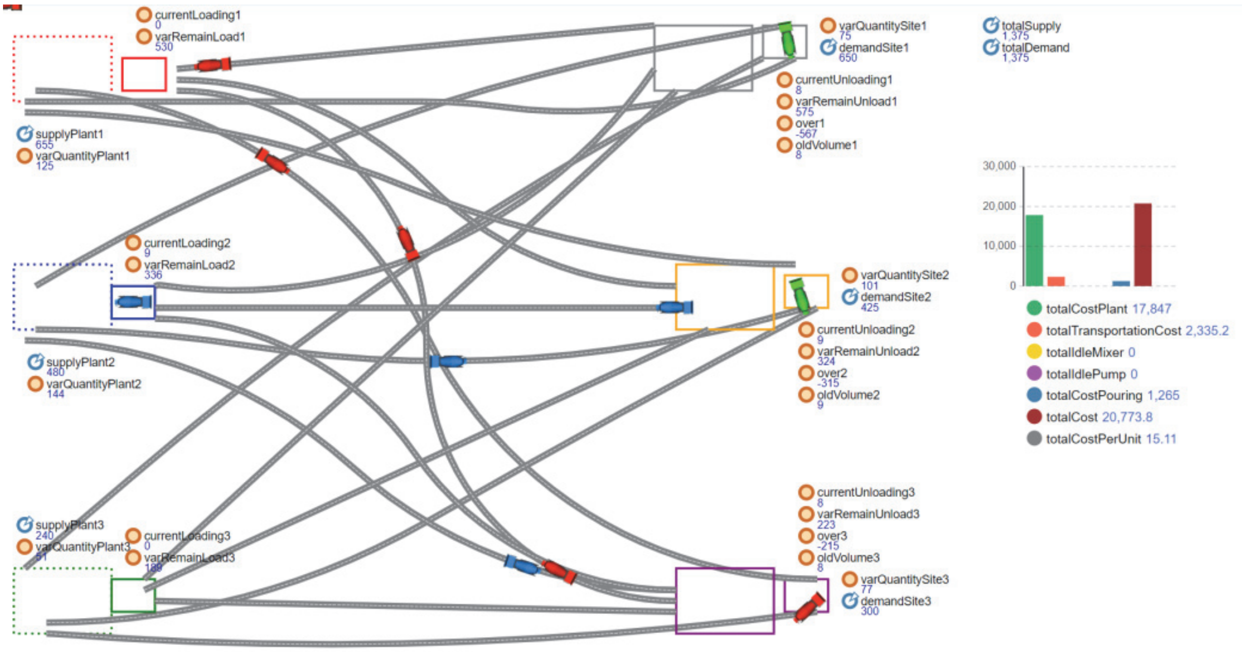

Figure 3 RMC supply chain process simulation model: 2D view during simulation

3.3 Presentation of the Model Output Data

Because of the probability and the stochastic nature of simulation modeling, every output parameter is a random variable. The degree of validity should be determined based on the reliability analysis conducted on the simulation model. The presented model yields a large amount of output data, which can be utilized depending on the need. Some of them are diagrams and charts showcasing cost structure (production, transportation, pouring, idling cost) at each separate construction site (Fig. 4), as well as the total for all construction sites (right hand side in Fig. 3), the number of truck mixers per each plant/site, the quantity of produced/poured concrete per each plant/site, the duration of loading/unloading/idling, the average truck mixer speed, etc. (Figs. 5 and 6). All output data shown in Figs. 4 to 6 were obtained from the analysis of the case study described in the following section below.

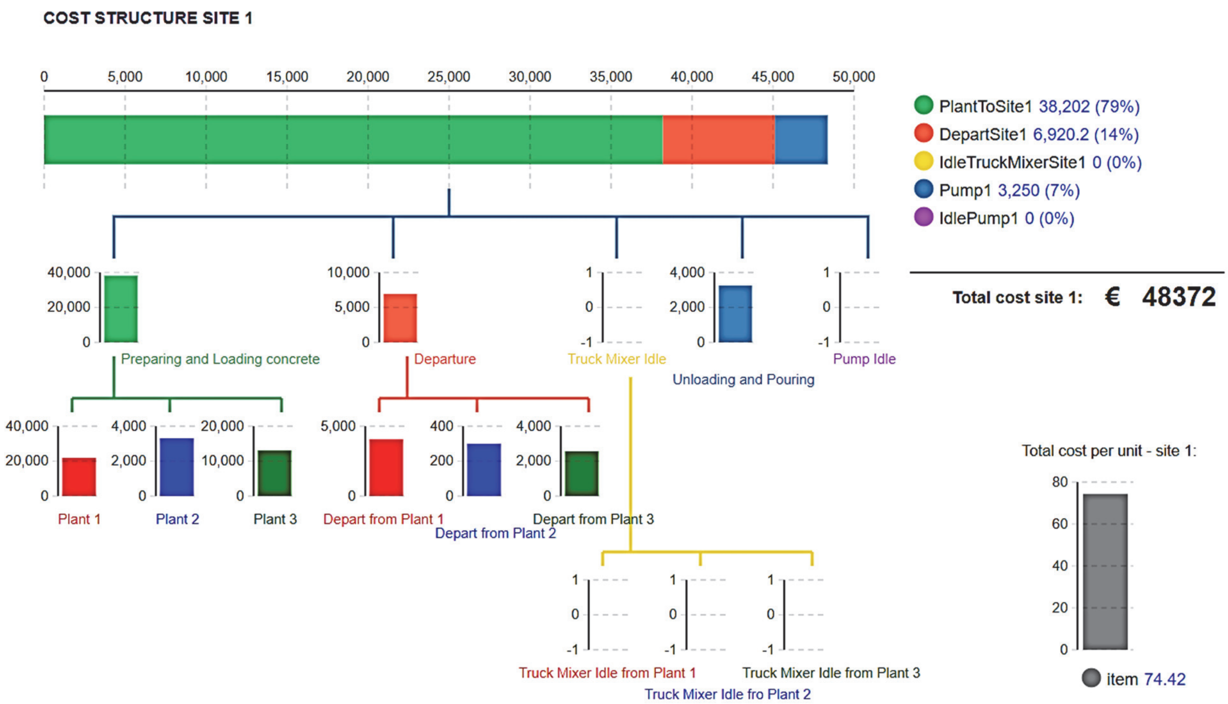

Figure 4 RMC supply chain process simulation model: cost structure - construction site 1

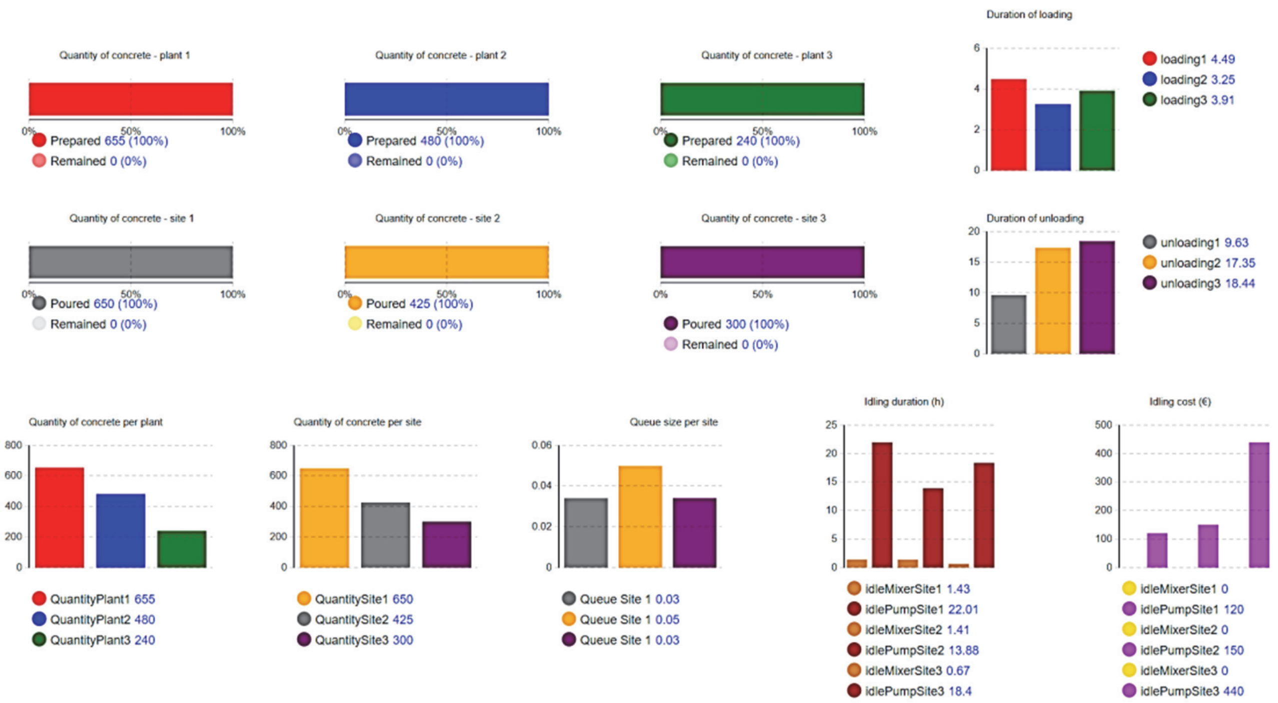

Figure 5 RMC supply chain process simulation model: diagrams for quantity of concrete per plant/site, duration of loading/unloading, and idling duration/cost

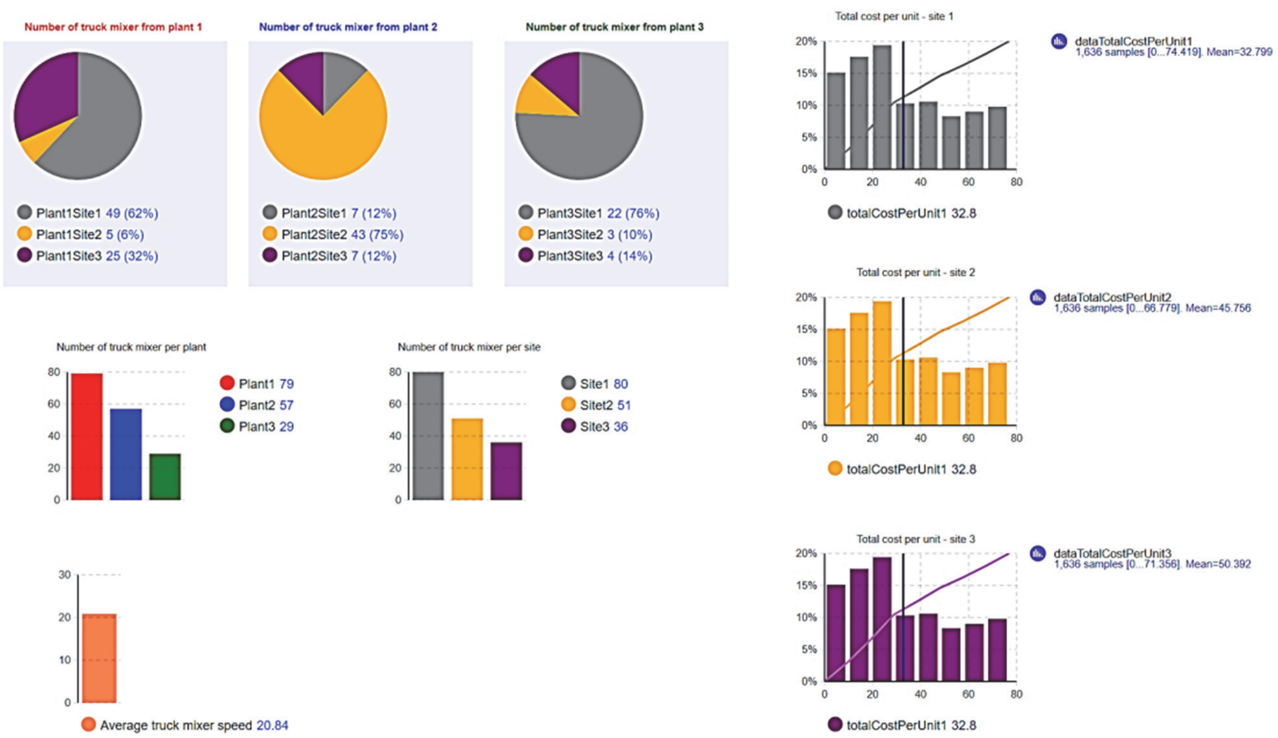

Figure 6 RMC supply chain process simulation model: diagrams of truck mixer number per plant/site, average truck mixer speed, and unit cost per site

4 CASE STUDY

To test and verify the developed simulation model, a case study analysis was performed. Program testing involves a formal verification of whether the program performs correctly with specified test data. Data were collected and the process of the selected study cases was recorded. The issue of input data accuracy is an important one for the ultimate validity of the model. Model results may be more sensitive to changes of some data and less so to changes of other data. By analogy, it is necessary to consider the required accuracy of input data. Likewise, it is also often impossible to collect certain input data, in which case it is necessary to resort to their estimation. Model validation refers to the verification of the results' agreement with the actual system or to the determination of whether the model is a sufficiently good abstraction of the actual system.

4.1 Description of the Case Study Problem

In the selected case study, there is a need for simultaneous concreting during construction work at three construction sites (construction site 1, 2, and 3), which are supplied with RMC from three concrete plants (concrete plant A, B, and C). Each site is intended for the construction of residential buildings with different floor number configuration, namely, site A: 2B + G + 6, site B: 2B + G + 6, and site C: G + 4. The supply quantities of concrete for sites A, B, and C are 650 m^3, 425 m^3, and 300 m^3, respectively. Google Maps locations of the concrete plants and construction sites in the city of Niš and its surrounding areas are shown in Fig. 7, whereas individual distances are given in Tab. 1.

Table 1 Distance from concrete plant to construction site / km

Constuction site/Concrete plant	1	2	3
A	10,6	9,9	13,2
B	5,2	7,2	3,0
C	11,9	10,1	13,5

Figure 7 Locations of the case study concrete plants and construction sites (city of Niš and surroundings, Serbia) in Google maps

Tab. 2 shows the required characteristics of the available machinery in each of the plants. Mobile pumps from plant A are used at site 1, those from plant B at site 2, and those from plant C at site 3.

Table 2 Available machinery of concrete plants

Concrete plant	Concrete plant production rate / m^3/h	Mobile pump production rate / m^3/h	Available truck mixers - number and volume / m^3
A	80	35	3 × 13; 5 × 10; 2 × 6
B	60	30	3 × 12; 2 × 9; 2 × 7
C	30	25	7 × 9

Table 3 Departure cost depending on the distance / €/m^3

Concrete plant	up to 10 km	10-20	20-30	30-40	40-50	over 50 km
A	7	10	13	15	17	20
B	5	9	12	15	17	20
C	8,9	14,2	18,7	21,6	24,7	26,2

Departure cost depending on the distance is shown in Tab. 3. Other input data in the experiment, such as cost of concrete production, cost of concrete pouring, as well as idling cost (truck mixer and pump), are shown in the input window of the simulation (Fig. 2).

Concreting work relied on continuous activity of 5 mixers from plant A, volume (1 × 13; 3 × 10; 1 × 6), 4 mixers from plant B, volume (2 × 12; 2 × 7), and 2 mixers from plant C, volume (2 × 9). Based on collected data, after recording the entire process, the following results were obtained: concreting duration was 29,1 h (1746 minutes), while concrete production costs were 79050 €, concrete pouring costs 6875 €, penalties charged due to pump idling 40 € (there was a single occurrence of exceeded allowed interval at site 3), and penalties charged due to mixer idling 150 € (three exceeded allowed intervals at site 1 and one at sites 2 and 3 each), while the transportation costs amounted to 12200 €.

4.2 Model Test and Results

The simulation experiment was conducted based on the data collected during the recording of the concreting process in the case study (the model was simulated 100 times). The obtained output data were processed statistically and compared against the data obtained from the actual process. In Tabs. 4 and 5, scenario 14 (red framed) refers to the output data from the simulation experiment of the case study. The collected data and the results from the simulation are not identical owing to the stochastic nature of the problem. Simulation yielded differences of 9,39% shorter duration, 1,04% lower transportation costs, 11,8% lower mixer idling costs, and 49% lower pump idling costs. The costs of concrete production and pouring were the same for the actual example and the simulation. For analytical purposes, the model accuracy is satisfactory, i.e., the results obtained from the simulation represent the approximate value of recorded data, so the model can undergo further testing.

4.3 Simulation Results for Different Combinations of Truck Mixers

To further test the model, to examine how different vehicle combinations influence the price, and to obtain the optimal scenario, an experiment was conducted with the same input data for the case study but with different truck mixer combinations (number and volume). Based on the available number and capacity of the truck mixers from the three plants, 25 fleet combinations that would yield acceptable results (minimum idling cost) were made. An experiment was conducted for each combination, which involved running the simulation 100 times, recording and statistically processing the results, after which mean values were calculated. Out of 25 combinations, six of them were selected, including the combination used in the case study (1, 2, 4, 11, 13, and 14), because they produced better results. In addition, an experiment was conducted with 11 more proposed combinations (3, 5, 6, 7, 8, 9, 10, 12, 15, 16, 17), only with mixer volumes and numbers that the given concrete plants do not possess. Again, the simulation was run 100 times for each combination and the mean values were calculated, yielding the costs for a total of 17 different combinations, as shown in Figs. 9 to 12.

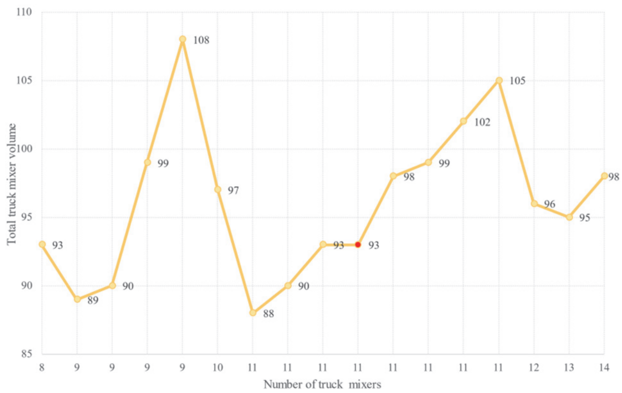

Figure 8 Total truck mixer volume depending on number of truck mixers

All combinations were made so that the total volume of truck mixers within the same concrete plant would be approximately the same (plant A 39-49 m^3; plant B 30-38 m^3; plant C 16-24 m^3). Tab. 4 and Fig. 8 show the considered fleet combinations, sorted according to the ascending order of the number of mixers and then according to the ascending order of volume within the same number.

Table 4 Fleet combination (input parameter for simulation experiment)

Scenario	Fleet combination	Number of truck mixer	Total truck mixer volume / m^3	Plant A		Plant B		Plant C	
				Truck mixer combination	Volume / m^3	Truck mixer combination	Volume / m^3	Truck mixer combination	Volume / m^3
1	332	8	93	3 × 13	39	3 × 12	36	2 × 9	18
2	342	9	89	3 × 13	39	2 × 9 + 2 × 7	32	2 × 9	18
3	432	9	90	4 × 10	40	3 × 10	30	2 × 10	20
4	432	9	99	1 × 13 + 3 × 10 + 1 × 6	49	2 × 12 + 2 × 7	38	2 × 9	18
5	432	9	108	4 × 12	48	3 × 12	36	2 × 12	24
6	442	10	97	2 × 12+2 × 10	44	2 × 10 + 2 × 8	36	1 × 9 + 1 × 8	17
7	542	11	88	5 × 8	40	4 × 8	32	2 × 8	16
8	542	11	90	2 × 8 + 2 × 9 + 1 × 7	41	2 × 8 + 1 × 9 + 1 × 7	32	1 × 8 + 1 × 9	17
9	542	11	93	3×9+2×8	43	3 × 8 + 1 × 9	33	1 × 9 + 1 × 8	17
10	542	11	93	3×8+2×9	42	2 × 8 + 2 × 9	34	1 × 8 + 1 × 9	17
11	542	11	98	1 × 13 + 2 × 10 + 2 × 6	45	1 × 12 + 1 × 9 + 2 × 7	35	2 × 9	18
12	542	11	99	5 × 9	45	4 × 9	36	2 × 9	18
13	542	11	102	4 × 10 + 1 × 6	46	2 × 12 + 2 × 7	38	2 × 9	18
14 (case study)	542	11	105	1 × 13 + 3 × 10 + 1 × 6	49	2 × 12 + 2 × 7	38	2 × 9	18
15	642	12	96	6 × 8	48	4 × 8	32	2 × 8	18
16	553	13	95	2 × 10 + 3 × 8	44	3 × 7 + 2 × 6	33	3 × 6	18
17	653	14	98	6 × 7	42	5 × 7	35	3 × 7	21

Table 5 Idling cost for different fleet size

Scenario	Fleet combination	Number of truck mixer	Total truck mixer volume / m^3	Transport cost / €	Truck mixer idle cost / €	Pump idle cost / €	Total idling cost / €	Duration / min
1	332	8	93	11 960,69	5,63	216,25	221,88	1866
2	342	9	89	11 984,11	35,87	84,78	120,65	1874
3	432	9	90	12 053,20	21,66	71,10	92,76	1743
4	432	9	99	12 007,94	107,44	56,86	164,30	1659
5	432	9	108	12 016,00	27,86	32,14	60,00	1553
6	442	10	97	12 057,29	51,18	38,24	89,41	1661
7	542	11	88	12 118,72	10,20	11,80	22,00	1697
8	542	11	90	12 114,89	20,53	13,86	34,39	1677
9	542	11	93	12 137,45	12,73	7,58	20,30	1639
10	542	11	93	12 115,00	9,55	4,55	14,09	1650
11	542	11	98	12 096,46	60,82	17,98	78,80	1607
12	542	11	99	12 101,53	48,69	6,70	55,39	1586
13	542	11	102	12 098,98	108,90	17,20	126,10	1589
14 (case study)	542	11	105	12 072,59	132,30	20,40	152,70	1582
15	642	12	96	12 088,00	107,18	56,70	163,89	1705
16	553	13	95	12 152,20	126,00	0,00	126,00	1625
17	653	14	98	12 152,20	103,39	0,00	103,39	1592

Tab. 5 shows the results of the experiment, but only a portion of the costs because of spatial constraints. The cost of concrete production and pouring is a constant value (it depends only on the quantity of concrete produced in a specific plant or poured at a specific site), which is why it is not shown in the table. For the case study, the total cost of concrete production for the considered quantities amounts to 79050,00 € and the total cost of concrete pouring amounts to 6875 €. The total cost (Fig. 11) is the sum of production, transportation, idling (pump and truck mixer), and pouring costs.

The costs of truck mixer idling, pump idling, as well as total idling (sum of truck mixer idling and pump idling) for different combinations are shown in Fig. 9, the transportation cost in Fig. 10, and the total cost in Fig. 11.

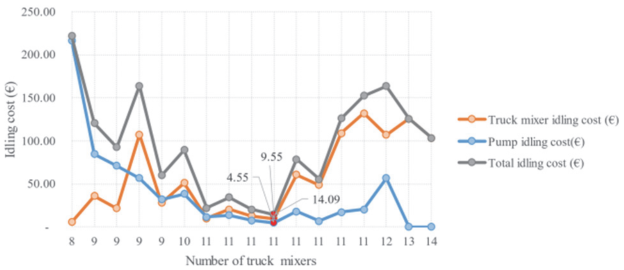

Figure 9 Idling cost for different fleet size

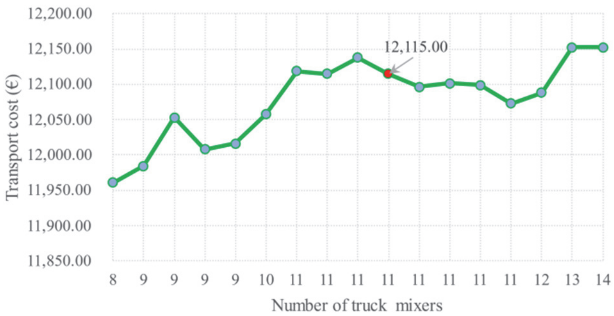

Figure 10 Transportation costs for different fleet size

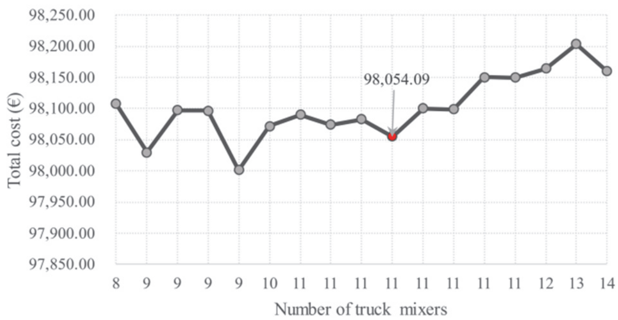

Figure 11 Total cost for different fleet size

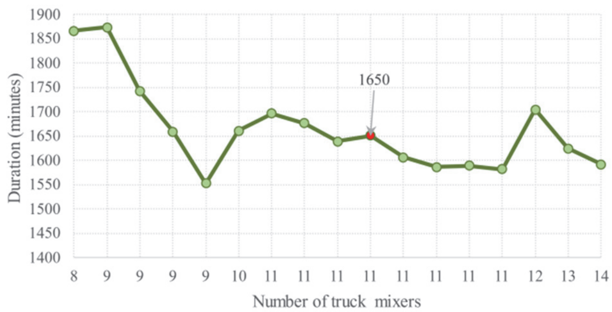

Figure 12 Duration of concreting for different fleet size

Fig. 12 shows the simulated duration of concreting depending on the applied combination. All Figs. 8 to 12 highlight the fleet combination that yields the lowest penalty cost (scenario 10).

4.4 Discussion of the Simulation Experiment Output Data

The developed simulation model attempts to improve the process of simultaneous RMC supply to three construction sites from three concrete plants by minimizing the time (and cost) of vehicle idling and the time (and cost) of pump idling at the site. For this purpose, different combinations of truck mixers were applied and the obtained simulation results were then tested.

The results of the simulation experiment with varying number of mixers indicate that there is a significant influence of vehicle number and volume on idling costs. According to Fig. 9, the increase of the number of vehicles also increases their idling cost, whereas the lower number of vehicles increases the pump idling cost. Lower total costs were observed for several combinations with 11 vehicles. It is noticeable that the increase of the number of vehicles slightly increases transportation costs (Fig. 10), while the duration decreases (Fig. 12). Transportation cost increase is minimal, the difference between the lowest (11960,20 €) and the highest (12152,20 €) transportation cost is only 1,58 %, which can be explained by the fact that charges are incurred by concrete unit of measurement. The number of vehicles affects duration decrease so that the waiting time for concrete significantly decreases as the number of vehicles increases, thus reducing the total time. However, prolonged waiting for a mixer to unload may lead to reduced concrete quality.

Based on the model analysis in the case study, scenario 10 is recommended as the optimal combination of truck mixers for the considered case study. This combination minimizes mixer and pump idling costs at the site (Fig. 9) but leaves transportation costs slightly higher (12115,00 €) (Fig. 10). Nevertheless, concreting duration is not the shortest in this scenario (Fig. 12), but in scenario 5, which also yields the lowest total cost 98001,00 € which is 0,05% less than the total cost in scenario 10 (98054,09 €). It is hardly feasible to achieve the minimum for all criteria (duration of work and all costs). The criterion for optimal choice may be different. Since the set goal is to find a fleet combination that would result in the lowest penalty cost for the given case, the combination in scenario 10 meets this criterion. The simulation results indicate that the selection of an adequate combination can significantly reduce the costs of idling, for both the mixer and the pump, which leads to minimal idling time and, consequently, to timely pouring of concrete without reducing its quality.

5 CONCLUSION

The developed model was aimed at improving the entire RMC delivery and supply process by minimizing idling time and idling cost. This paper showed that RMC delivery simulation can produce useful and relevant information for the construction industry. The presented study is relevant in so far that the RMC delivery process was represented using a simulation model that can be efficiently implemented in the concrete supply process.

The goal is to minimize penalty costs (due to pump and mixer idling) and enable the selection of the optimal concrete supply scenario. An experiment was conducted to show the influence of different truck mixer combinations on costs and duration of the process. The model was developed to simulate an RMC supply chain from a maximum of three concrete plants to a maximum of three construction sites, which is the limitation of the model, using multiple truck mixers with various volumes, but it can be used for any other combination of plant and site numbers (e.g., two plants - one site, one plant - three sites, etc.). The model was verified through comparison of the simulation results against the actual situation (recorded data) in the case study. The model is applicable to any study with input parameters characteristic of the analyzed situation. At the beginning of the simulation experiments, the necessary data are fed, while fleet size and volumes of truck mixers are defined prior to the experiment. The model is also applicable to different analyses and parameter variations with detailed output data.

Generally, the proposed model is a practical tool for decision makers regarding optimal planning of concrete works with minimized costs. The model can be used to create an optimal plan of simultaneous RMC supply from different plants to different sites while ensuring continuity of concrete production and pouring, whereby the reduction of machinery idling reduces the total cost and improves work quality. The computer program for the model is user friendly and is designed so as to aid managers to simplify cost prediction and calculation. The model utilizes the simulation technique to find the optimal schedule of supply to construction sites and to minimize mixer/pump idling at the site, thus meeting the site demands. The simulation model was created using input data based on functions that describe plant and pump operation and truck mixer speed, which is another constraint of the model. But the model can be customized to meet different needs through quick and easily-made modifications of the data. Therefore, the simulation model could be used as a decision-making support tool for the selection of an adequate dispatch scenario for RMC delivery. Similarly, simulation results could be used to estimate the number of vehicles necessary to complete a delivery order.

Further research can be directed towards experiments for the same case study presented in this paper, but with concrete supply from only one or two plants, the results of which could then be compared against the results of this study. Additionally, the plan for future research is to analyze the model with different parameter variations, to implement the model, to upgrade it, and to include new variables that would represent the problem more precisely and more comprehensively.

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