BULLETIN OF THE POLISH ACADEMY OF SCIENCES
TECHNICAL SCIENCES, Vol. 68, No. 5, 2020
DOI: 10.24425/bpasts.2020.134643

CIVIL ENGINEERING

Road vehicle sequencing problem in a railroad intermodal terminal – simulation research

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Abstract. The paper presents the issue of container handling processes at a railroad intermodal terminal. The main purpose of this paper is the assessment of the handling equipment utilization and the associated energy consumption. The authors analyze how the road vehicle availability at the moment specified in the containers loading schedule influences the total handling equipment operation time as well as the necessary number of handling equipment. It is assumed that vehicles planned for loading of import containers may be late for loading, which causes some interruptions in the loading schedule. Such interruptions are identified with the necessity to handle the next container for which the road vehicle is already waiting, which influences the handling equipment utilization and, finally, energy consumption. The general mathematical model of the problem developed in the FlexSim simulation software was presented. Based on the simulation research, it pointed out that proper road vehicles loading sequencing can significantly reduce handling equipment operation time, and thus energy consumption, costs, and CO_2 emissions. The literature analysis presented in the paper indicates that most of the research in the field of intermodal transport is focused on operations optimization in container ports. There are differences between two types of intermodal terminals in operation procedures and rules. That is why the authors decided to undertake the problem of road vehicle sequencing including their random availability and its influence on handling device operation time, which has not been considered in the literature so far.

Key words: intermodal terminal, road vehicle sequencing, FlexSim simulation, modelling.

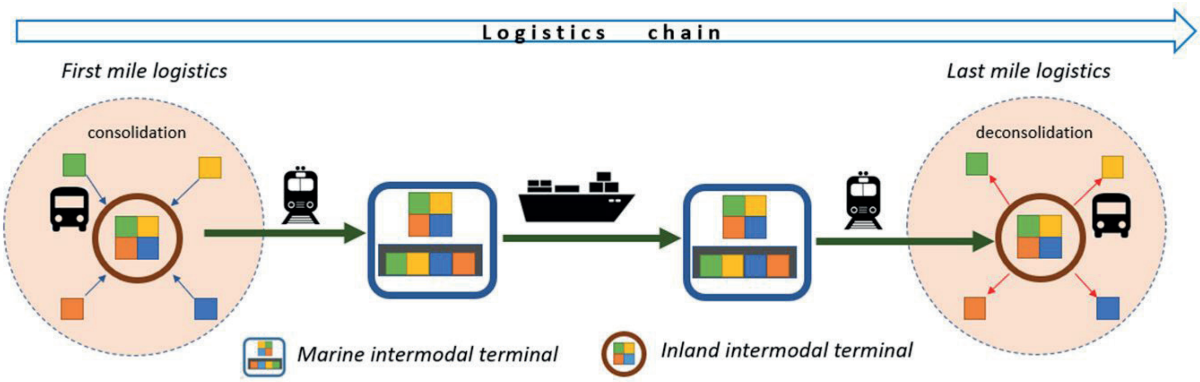

Fig. 1. Intermodal transport idea

1. Introduction

The starting point for the considerations in this paper is intermodal transport, which is the result of the containerization that has been developing since the mid-20th century and the overall increase in goods transport. Also, technological progress in transport and the intensive development of railroad transport technologies is significant here.

Intermodal transport involves the transportation of freight in an intermodal container or a vehicle, using multiple modes of transportation (e.g., rail, ship, and truck), without any handling of the freight itself when changing modes. It enables a combination of the strengths of various modes of transport and, as a result, achieve a synergy effect in the form of increased transport efficiency and reduction of its external costs. All these features make intermodal transport an increasingly important part of the logistics sector.

The general idea of intermodal transport can be presented as in Fig. 1.

As presented in Fig. 1, a really important element of intermodal transport is road transport. Due to its availability, it can perform door-to-door services. Road vehicles deliver intermodal transport units to the transshipment terminal at the first mile and to final customers at the last mile of a logistics chain. Efficient consolidation and deconsolidation of loads as well as the service

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Manuscript submitted 2020-01-17, revised 2020-03-28, initially accepted for publication 2020-04-02, published in October 2020

of road vehicles in the transshipment terminal, directly affect the efficiency of cargo flow throughout the entire logistics chain.

The basic function of the transshipment terminal (intermodal terminal) is to allow the intermodal transport units loading and unloading as well as to change the mode of transport. As reported in [1], such terminals are usually located close to large industrial centers, ensuring the loading services of these areas. In addition, the largest of them are usually part of seaports servicing intermodal units in worldwide transport.

According to the definition adopted by the European Conference of Ministers of Transport (ECMT), the United Nations Economic Commission for Europe (UNECE) and the Organization for Economic Community and Development (OECD), the *terminal is an area intended for the storage of intermodal transport units, equipped with proper ITU handling equipment*. This definition was refined in [2]. The author assumes that an intermodal terminal is a spatial facility with its proper organization and infrastructure enabling the transshipment of intermodal transport units: containers, swap bodies and semi-trailers between means of transport belonging to different modes of transport as well as enabling operations performed on these units (operations regarding, e.g. storage).

Intermodal terminals can be divided into railroad and marine terminals. In the first case, we deal with terminals located in the railway network with access to road infrastructure. In the second case, however, these are terminals located in seaports and constituting a part of the port. Marine intermodal terminals, due to their functions in intermodal transport, have access to both rail and road transport infrastructure, and in some cases, inland waterway infrastructure. In addition, such terminals are equipped with their own warehouse facilities, which facilitate the provision of services related to the consolidation of general cargo in containers.

As reported in [3], intermodal transshipment terminals play an important role in railroad transport, performing the following functions:

– Transshipment of intermodal loading units in various transition relationships through the terminal. Transshipments depending on the loading units service technology can be conducted both directly and indirectly with operational storage.
– Operational and rotational storage of intermodal loading units.
– Logistic support of the transport chain (sorting of intermodal loading units, quality control, customs, and border clearance).
– Providing additional services (current maintenance, repair, and cleaning of intermodal loading units).

Based on the above, the general task is to handle import and export containers. Import containers are delivered to the terminal by rail transport. Export containers are sent from the terminal by rail transport.

Generally, after the train arrives at the intermodal terminal, container rail cars are unloaded. Containers are transferred directly to road vehicles (container semitrailers) or the storage yard. It means that some transshipments are direct (rail car – truck), called direct moves and some of them are indirect (rail car – storage yard – truck), called split moves.

Since containers in the storage yard are stacked on top of each other, it is necessary to plan their arrangement. As it was noted in [4], this arrangement should take into account containers gross weight (heavier container should not be stored on a lighter container), maintaining stability (container 40' cannot be stacked on two 20 'containers and vice versa), expected date of container departure (in order to avoid moving containers in the yard, which in the literature is called *reshuffling*).

In most intermodal terminals, container export operations are usually performed after the import operations are completed. Of course, to increase the efficiency of handling processes, mixed operations are also acceptable. The delivery of a container by a road vehicle before the train arrives means that the container needs to be stored. Only after the train arrives, the container can be moved from the storage yard onto the train. Then a space along the rail car is made available for the vehicle with the container ready for handling. These types of operations are rare. This is mainly due to the container handling strategy at the intermodal terminal and associated costs.

The rapid development of worldwide container transport, as well as the increasing volume of inland transport with the use of intermodal transport units, generates higher demand for handling efficiency of railroad intermodal terminals. Intermodal terminals, where the operations performance strategy is based on the experience of terminal managers, may not be using the full capacity of the terminal as well as the full efficiency of handling equipment. Since most of the operations performed in the intermodal terminal relate to intermodal transport units handling, railroad terminals should focus on the optimization of a handling equipment utilization to improve handling efficiency, as well as considering sustainable development to reduce energy consumption.

The handling equipment utilization is the main purpose of this article. In this paper, the road vehicle loading sequencing problem arising from the crane scheduling problem in railroad intermodal terminal is considered. We analyze how the availability at the terminal of road vehicle planned for loading of import containers in the loading schedule influences the handling equipment (crane) utilization. We assume that the vehicles planned for loading import containers may be late for loading, which causes some interruptions in the loading schedule. Such interruptions are identified with the necessity to handle the next container for which the road vehicle is already waiting. We also analyze the energy consumption in import container loading operations and determine the key factors for improving energy efficiency. For the purpose of the research, the general import container loading optimization model is proposed considering the stochastic character of data related to arrival moments of road vehicles to obtain an approximate optimal road vehicle loading sequence. The rest of the paper is organized as follows: next paragraph is a review of the literature concerning intermodal transport units handling processes in the railroad terminal. The problem description is presented in Section 3. Section 4 contains the description and formulation of an optimization model of the analyzed situation. The simulation model of the analyzed situation based on real observations was developed and examined in Section 4. The final Section includes the conclusion.

2. Literature review

Because of the above-mentioned rapid development of container transport, intermodal transport has been largely studied in recent literature. The analysis of the literature facilitates distinguishing three main areas of research related to intermodal transport [5–8]: intermodal network design, intermodal terminal location, intermodal terminal operations and intermodal transportation routes optimization. In this article we focus on processes performed at intermodal terminals. The literature regarding these processes mainly focuses on marine intermodal terminals. The literature on container terminals in seaports is very wide and concerns processes connected with container ship operations such as: berth allocation and scheduling [9–11], quay crane scheduling [12, 13], ship stowage planning [14], storage yard processes optimization [15], and yard crane allocation and scheduling [16, 17].

There exist a few research papers on operational decision problems in rail terminals [18], on container operations in harbors [19], on crane scheduling in container ports [10, 20] and on crane scheduling under non-crossing constraints [21].

In the case of land-based intermodal terminals, the literature is not so rich. The literature on operation optimization of railroad intermodal terminal is relatively scarce. Although railroad and marine terminals operate with containers and have similar equipment, the specific operational procedures and rules are not the same. The main difference is related to quay crane operations in marine terminal and gantry crane in inland terminals. The quay crane area and a storage yard of the container port are compressed into one handling area in a railroad terminal. In the railroad terminal a crane is responsible for all the operations connected with containers loading and unloading as well as containers storage and reshuffling in the storage yard. This is the reason why the crane operation in the railroad terminal is much more complex than in the marine terminal. Moreover, research achievements in container terminals in marine ports cannot be directly applied in railroad intermodal terminals.

In the inland intermodal terminal transport of a container through the terminal with the use of a storage yard a few related decision problems are generated:

– Designation of storage position of containers handled by split moves;
– Intermodal train loading;
– Gantry Crane scheduling.

Containers handled by split moves must be stored in the storage yard. The aim is to find the best positions for containers considering the criteria such as maximization of the storage space and minimization of the necessary operations performed on a given container. The problem of containers positioning in the storage yard was extensively investigated for maritime intermodal terminals. A review of different approaches to this problem can be found in [22–24].

Another important issue arising in rail terminals is the intermodal train loading. To solve this problem, it is necessary to decide on the positions of containers on trains. Given the number of rail cars and their pin configuration as well as the number of containers that must be loaded on these rail cars, the problem is to minimize the number of rail cars per train. Constraints imposed can also refer to total loading time, container weight distribution on the train, and train aerodynamics, among others. This problem was recently investigated in [3, 25–28].

The issue that is considered in this article refers to the crane scheduling problem. It arises every time the container must be picked up and put down. The main element of this problem is to assign crane to the specific part of a loading/unloading/storage area where the containers meant to be handled are stored or waiting for train/truck loading/unloading and then to set the containers handling order. Due to the length of the train composition and the storage yard, to accelerate the implementation of loading works more than one crane is used to service containers. Cranes work in parallel based on the tasks assigned to them. Since cranes travelling along the storage yard cannot pass each other, their working area is limited to a separate Section of the storage yard. Tasks for cranes can be allocated statically or dynamically. In the case of static assignment, a crane that has completed all tasks does not take on the tasks of another crane. The method for cranes allocation was presented in [29]. As it was reported in [30], this type of allocation based on a prepared loading plan is most used. However, in the case of dynamic allocation, a crane that has completed its tasks may begin to perform other crane tasks. This type of approach to the problem of task allocation for cranes requires real-time task control.

After the crane allocation, crane sequencing is performed. The aim of sequencing crane moves is to determine the containers handling order. These problems are usually considered together. Tasks assigned to cranes can vary over time, especially when the operation performed on a road vehicle (its unloading or loading) is part of the task.

The literature on crane scheduling problem generally concentrates on quay crane scheduling but also on the gantry crane scheduling in railroad intermodal terminals. The author of [31] was one of the first considering the quay crane scheduling problem. In detail, it was presented in [32]. Because of its complexity, many authors proposed different heuristic algorithms such as tabu search heuristic [33] and genetic algorithms [34] to solve the problem. A series of improved models based on [35] have been proposed to handle the QCSP and obtained very good performance with standard solvers [36]. In recent years scientists have begun to consider some holistic approaches referring to crane scheduling together with truck transportation [37]. Nevertheless, the presented approach (a MIP model for a combined quay crane and yard truck scheduling problem with unloading inbound containers) cannot be directly applied to railroad terminals.

The problem of crane scheduling also arises in rail-rail terminals. The authors of [18] summarize the problems that can occur in such a terminal. Another publication of this author (see [38]) considers integrated gantry crane and shuttle car scheduling problem. In [39], the author considered a gantry crane scheduling problem with overlapping crane areas. In [40], the author constructed a simulation model of transferring cargo between trains, which was then used to evaluate different gantry crane operation modes. The problem of crane scheduling in railroad terminals has not been widely considered in the literature so far. In the railroad terminal this problem becomes more difficult than in other types of terminals because crane operations must include road vehicles service. Unfortunately, road vehicles may be late for the loading/unloading planned in the crane schedule. This results in the necessity to take up servicing of the next container/intermodal unit on which the road vehicle awaits loading/unloading at the terminal. Therefore, the crane handling sequence may change over time. In the railroad terminal this problem was investigated in [41, 42]. The authors of [42] propose a holistic approach, which jointly determines load plans, crane split, and crane move sequence. The authors determine follow-up destinations of trains, so that the number of resulting container moves is minimized. This problem is solved as a linear assignment problem. In detail, the problem of crane sequencing in the railroad terminal undertaken in [43]. The author of [44] proposed a bee colony algorithm to solve the crane scheduling problem. The approach presented in [45] uses the genetic algorithm to obtain the optimal handling sequence for the gantry cranes. Moreover, in [46] the authors proposed a two-way bounded dynamic programming approach to deal with the static crane scheduling problem encountered in both rail-rail and railroad container transshipment yards. The authors report that the designed exact solution algorithm solves instances of practically relevant size within acceptable time limits. They also recommend using a heuristic algorithm for planning very large transshipment yards, with more than five tracks and a large number of container moves per crane. This problem may also be considered like other scheduling issues. An example would be a cross-docking facility where vehicles are sequenced and assigned to loading gates in a time regime. In this issue, for example, simulated annealing or tabu search method is used [47].

Optimization of operations performed in the intermodal terminal has a huge influence on handling equipment efficiency and finally, energy consumption. Most publications regarding energy consumption refer to marine intermodal terminals. For example, in [48] the energy consumption of quay cranes is studied. The authors formulated the crane scheduling problem as a mixed integer programming model whose two objectives minimize the total completion delay of all task groups and the total energy consumption of all quay cranes. In [49], the authors proposed an integer programming model to solve optimal problem of yard crane scheduling with minimal energy consumption at container terminals from the low carbon perspective. An optimal model was built with consideration of such key factors as the crane moving distance, turning distance and the practical operation rules, which are directly related to the total energy consumption. In [50] the author investigates a problem of integrated berth allocation and quay crane assignment for the trade-off between timesaving and energy-saving. This problem is formulated as a mixed integer programming model (MIP), to minimize the total departure delay of all vessels and the total handling energy consumption of all vessels by quay cranes. In [51] the authors proposed a mathematical programming model for the quay crane assignment problem, in which the queueing theory is used to model the queueing behavior of automatic guided vehicles (AGVs). The objective of the proposed model is to minimize the energy consumption as well as the CO_2 emission during an unloading process of containers from quay cranes to AGVs by optimizing the number of quay cranes.

In the railroad terminals, the energy consumption of the handling equipment and the CO_2 emission was investigated in [3]. The authors considered the problem of intermodal train loading and the energy consumption of gantry cranes. The solution obtained for an electrical RTG crane was then compared with other sources of energy.

The above literature review indicates that most of the research in the field of intermodal transport is focused on operations optimization in container ports. Because of differences between two types of intermodal terminals in operation procedures and rules, the existing studies are hardly ever directly applied to railroad intermodal terminals. There is scarce literature on railroad intermodal terminals. The utilization of intermodal terminal handling equipment and its energy consumption was much more investigated for marine intermodal terminals. Publications on crane scheduling do not consider road vehicle transport, which is a very important element of railroad terminal operations.

3. Problem description

In this paper, we consider crane scheduling together with road vehicle loading sequencing. We focus on the influence of the irregularity of road vehicle arrival on the utilization of cranes while performing container loading operations and the energy consumption resulting from this utilization.

All the containers moved through the terminal can be divided into import and export containers. Export containers are sent from the terminal by rail transport. Import containers are delivered to the terminal by rail transport and then transshipped to their destination by road transport (road vehicles usually belonging to road transport carriers). In this paper, we focus on the operations performed on import containers. As road vehicles assigned by consignees arrive randomly to pick up specific containers, there is some uncertainty about which container will be picked up first before another one. This uncertainty may result in a great number of unproductive handling equipment moves, which influence the equipment utilization and finally energy consumption. To solve such a problem, a booking system for picking up import containers is usually used to collect information in advance and to reduce the uncertainty of container pick-up time. Based on the booking system data, the containers loading schedule is prepared. According to the plan, containers are sequentially loaded at the road vehicle operation line onto vehicles ready for loading (already waiting at the terminal, see Fig. 2). Usually the crane operator prepared for container loading calls the road vehicle driver and gives him information about the specific place of loading in the road vehicle operation line. Unfortunately, despite the prepared loading plan, there might occur some irregularities resulting from the possibility that some road vehicles can be simply late for loading. It means that if a given container scheduled in the loading plan cannot be loaded, the crane operator must proceed to the

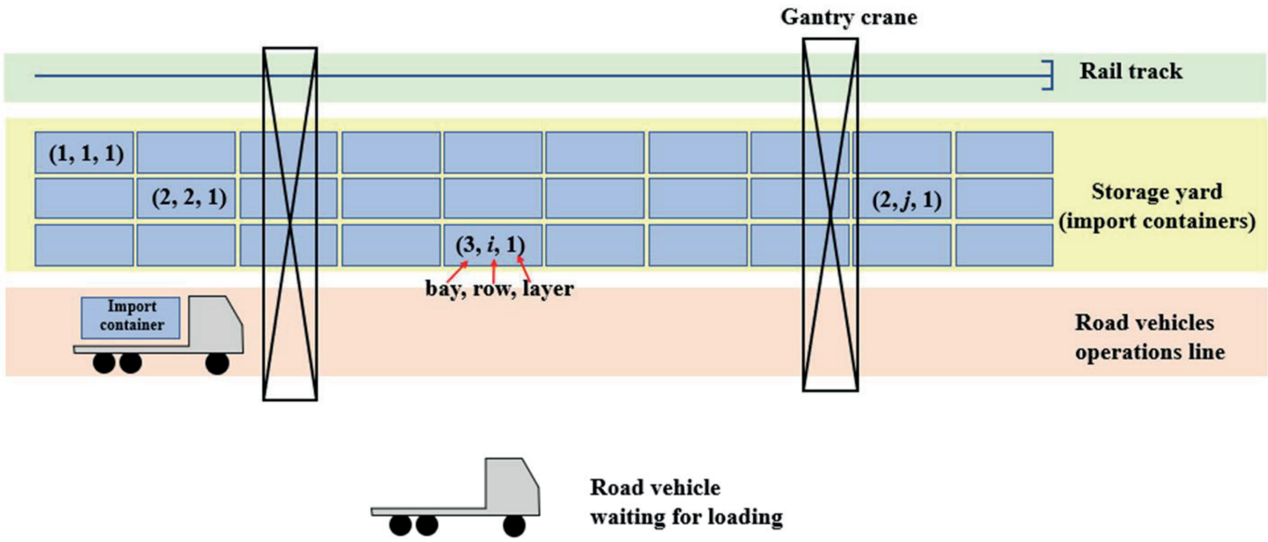


Fig. 2. Rail-road terminal area considered in the article

next container from the loading plan. It causes empty moves of a crane and reduces its efficiency. Moreover, the container that has not been loaded will be loaded later (when the late vehicle arrives). In this article we assume that a road vehicle can be late for loading.

The key issue for improving the energy efficiency of import container loading in railroad intermodal terminals is to reduce the empty move distance of gantry cranes while handling containers. Therefore, the optimization objective of our study is to optimize the import container loading sequence to minimize the handling move distance. Decreasing the energy consumption from empty crane movements can be effective in improving the energy efficiency of import container loading in railroad intermodal terminals.

4. Mathematical problem formulation

List of symbols and notations used in mathematical formulation:

- V – set of vehicles, v – vehicle number,
- C – set of cranes, c – crane number,
- S – set of services, s – service number,
- K – set of containers, k – container number,
- I – set of vehicle service fields at handling area, i, j – field numbers,
- $z(i, v, k)$ – variable defines when the k-th container is loaded on v-th vehicle at i-th service fields,
- $p(c, s, k)$ – variable defines when the k-th container is loaded during s-th service by c-th crane,
- $d(i, j)$ – distance between service fields $(i, j \in i)$,
- dm – average distance passed during each service by crane trolley,
- $t(i, j)$ – travel time between service fields,
- tm – average travel time of crane trolley during each service,
- $TW(k)$ – random waiting time for the vehicle on which k-th container must be loaded; it is also a component of the crane's idle time,
- $y(s)$ – service field number assigned to perform s-th service,
- $q(v)$ – vehicle capacity,
- $\alpha(c)$ – beginning of the area (number of the first field in the handling area) served by the c-th crane,
- $\beta(c)$ – end of the area (the number of the last field in the handling area) served by the c-th crane.

The described decision problem is related to the crane scheduling problem, including the issue of resource assignment to tasks. In the mathematical model included the main sets of elements of the intermodal terminal system. The set of vehicle numbers was written as $V = \{v:\ v = 1, \ldots, \overline{V} \ \wedge\ v \in \mathbb{Z}^+\}$, set of cranes $C = \{c:\ c = 1, \ldots, \overline{C} \ \wedge\ c \in \mathbb{Z}^+\}$ and also the set of service number $S = \{s:\ s = 1, \ldots, \overline{S} \ \wedge\ s \in \mathbb{Z}^+\}$. During the s-th service, the k-th container will be loaded, the set of containers for loading was written as $K = \{k:\ k = 1, \ldots, \overline{K} \ \wedge\ k \in \mathbb{Z}^+\}$.

The vehicles arrive at the handling area to a specific place. These places take the numbers from the set $I = \{i:\ i = 1, \ldots, j, \ldots \overline{I} \ \wedge\ i \in \mathbb{Z}^+\}$. It is also necessary to specify a table linking the number of the place in the handling area with the number of the vehicle which will be loaded and the number of the container as $Z = [z(i, v, k):\ z(i, v, k) \in \{0, 1\}]$. This value belongs to binary numbers and takes 1 when the k-th container is loaded at the i-th place for the v-th vehicle, 0 otherwise.

During the vehicle loading, the crane travels the distance between fields in the handling area, which is written as $d(i, j)$, where $i, j \in I$. The crane must pass this distance between subsequent services, but if the following services are provided in the same field, the length is equal 0. The field number in the handling area will be associated with the service number, $y(s) \in I$ and $y(s)$ will mean the number of the field in which the vehicle should be during the s-th service. Moreover, the trolley moving while the container is picked up, in the model it was written as the average distance passed by the crane trolley to move the container from the storage yard to the vehicle (including the operation of moving colliding containers). This average distance was written as *dm*.

Container handling is related to the time it takes to complete this operation. Time for travelling of the crane between the fields was determined as $t(i, j)$, and *tm* as the average time of container loading operations. In addition, the vehicle wait time was added as a random variable $TW(k)$ dependent on the k-th container. If all vehicles are waiting in the square, this value is always 0. Its inclusion allows considering different variants of the strategy for determining the waiting time for a vehicle or skipping vehicle service.

Based on the above, a criterion for assessing the implementation of container operations was formulated as the distance covered by all cranes (1), and the total time as (2).

$$D = \sum_{c \in C} \sum_{s \in S} \sum_{k \in K} p(c, s, k) \left[d\big(y(s-1), y(s)\big) + dm \right] \tag{1}$$

$$T = \sum_{c \in C} \sum_{s \in S} \sum_{k \in K} p(c, s, k) \Big[t\big(y(s-1), y(s)\big) + \\ + tm + TW(k) \Big] \tag{2}$$

$$P = \left[p(c, s, k): \quad p(c, s, k) \in \{0, 1\} \right] \tag{3}$$

In the model, the decision variable determining the plan of vehicle services was included (3). The set of decision variables is an array specifying the order of container handling, wherein $p(c, s, k)$ has value 1 when the c-th crane in the s-th service operates loading the k-th container onto the vehicle, 0 otherwise. In addition, as a related variable, the container number handled during the s-th operation was written as $h(s) \in K$.

The formulation of the problem requires the definition of boundary conditions. For general formulation, the following relations were developed:

$$\forall k \in K \quad \sum_{c \in C} \sum_{s \in S} p(c, s, k) = \sum_{i \in I} \sum_{v \in V} z(i, v, k) \tag{4}$$

$$\forall c \in C \quad \forall s \in S \quad \sum_{k \in K} p(c, s, k) = 1 \tag{5}$$

$$\forall s \in S \quad \sum_{c \in C} \sum_{k \in K} p(c, s, k) = 1 \tag{6}$$

$$\sum_{s \in S} \operatorname{sgn}\big(y(s)\big) = 1 \tag{7}$$

$$\forall k \in K \quad \sum_{i \in I} \sum_{v \in V} z(i, v, k) = 1 \tag{8}$$

$$\forall v \in V \quad \sum_{i \in I} \sum_{k \in K} z(i, v, k) \le q(v) \tag{9}$$

$$|S| = |K| \le \sum_{v \in V} q(v) \tag{10}$$

$$\alpha(c) \le \beta(c) \tag{11}$$

$$\text{if } |C| \ge 2 \text{ then } \beta(c) < \alpha(c+1) \tag{12}$$

Equations (4–6) specify that one container can be loaded only onto one vehicle during the service performed by one crane and the crane during one service can move one container to one vehicle. For one service one manipulation field is assigned (7). One container is assigned exactly to one vehicle and to one place for the handling area (8), and each vehicle has a limited capacity (in containers) (9). The constraints on the load capacity can be used to expand the model with the use of containers of various sizes and weights. The number of services is equal to the size of the container set, and thus all containers will be scheduled for loading, but must be less than or equal to the sum of the vehicle capacity (10). The crane working area was indicated as the constraint (11) and when there are two cranes or more, another constraint must be met (12). It has been assumed that each crane has a specific area which starts at $\alpha(c) \in I$ and the ends at $\beta(c) \in I$, however, these areas must not overlap, the beginning of the area is served by the first crane, i.e. $\alpha(1) \in 1$ and the end of the area by the last one i.e. $\beta(\bar{C}) \in \bar{I}$. In any modifications, the crane working area can be allocated dynamically depending on the current state and situation in the system.

The model presented above can be extended with the characteristics that improve the interpretation of the conducted research. Such characteristics include, for example, energy or fuel consumption (13), costs (14) or the emission of harmful substances (15). Assuming unit values such as: $fc(c)$ which is fuel or energy consumption for c-th crane; $fk(c)$ is a cost of fuel used by the c-th crane, $ue(c)$ unit emission from used energy, indicators were formulated as follows:

$$FC = \sum_{c \in C} fc(c) \sum_{s \in S} \sum_{k \in K} p(c, s, k) \cdot \\ \cdot \left[t\big(y(s-1), y(s)\big) + tm \right] \tag{13}$$

$$COST = \sum_{c \in C} fc(c) fk(c) \sum_{s \in S} \sum_{k \in K} p(c, s, k) \cdot \\ \cdot \left[t\big(y(s-1), y(s)\big) + tm \right] \tag{14}$$

$$EM = \sum_{c \in C} fc(c) ue(c) \sum_{s \in S} \sum_{k \in K} p(c, s, k) \cdot \\ \cdot \left[t\big(y(s-1), y(s)\big) + tm \right] \tag{15}$$

Considering such characteristics facilitates a better assessment of the impact of decisions made on the functioning of the container terminal. At the same time, their application allows determining the scale of possible savings when implementing solutions to improve the operation of the terminal. The functions (13–15) do not include the time $TW(k)$, which is the idle time and does not affect their value. However, it is possible to extend the cost function with this component in the aspect of dwel time and the costs connected with it.

The developed model is general, and its purpose is primarily to present the characteristics of the decision problem. Depending on the needs, it can be specified to study the specific phenomena or support in a particular decision problem. Among the significant modifications and extensions that can be made as indicated:

- Considering the criterion function in terms of the work performed by each crane together with the problem of minimizing the number of cranes and service time;
- Determination of vehicle sequence and arrival time window definition;
- Considering random variables such as loading operation time and waiting time for the vehicle;
- Considering the aspect of taking the container from the storage yard, and thus specifying the method of calculating the time specified as tm and distance tm (considering the need to conduct several container operations to get the desired container out of the storage yard);
- Dynamic allocation of areas served by a given crane, depending on the current situation.

The developed model presents the main elements of the intermodal terminal system that should be considered to properly investigate the issue of arranging the order of service of road vehicles. The next part of the article presents a specific problem based on a real example in the form of a simulation model in the *Flexsim* environment.

5. Simulation model

In recent years to improve logistic processes and transport means, scientists very often use simulation tools and advanced algorithms, see [52–55]. This is due to the stochastic nature of the input data to the problems and the need to implement transport and handling processes in real time [56].

Usually, simulation methods are used to analyze the performance of the intermodal terminal in terms of the location of the terminal functional areas or the efficiency assessment of the handling equipment. The simulation is used to test optimization methods and algorithms before they are implemented in intermodal transport units flow management and control systems in the terminal. Simulation models of the selected processes performed in the intermodal terminal were formulated in [57–60]. Most of the literature regarding simulation research focuses on AGV usage in marine intermodal terminals.

The problem of road vehicles loading in the intermodal terminal is not an easy issue. Difficulties in the road vehicles loading planning arise from the possible lack of readiness of road vehicle for loading. A road vehicle simply can be late for the planned loading. This is because road vehicles are the property of external carriers (usually many different carriers) employed to deliver containers to final customers.

The idea of road vehicle loading planning is to minimize the cost associated with the distance covered by the handling device (usually a crane or a reach stacker). In theory, based on the list od intermodal transport units meant to be delivered to final customers, it is possible to plan the road vehicle loading in such a way that the loading sequence of intermodal transport units is based on the distance between them in the storage yard. Such an approach to road vehicles loading is possible assuming that the road vehicles are waiting in the terminal and can be called for loading any moment. In such a case the handling device distance is easy to be minimized. If the road vehicle is not ready for loading (did not reach the terminal), the handling device operator must start the next (i+1) intermodal transport unit service (because the vehicle for a given unit is already waiting), skipping the unit number i. An additional distance is generated by the handling device, which will later have to "go back" to service the late road vehicle. The number of intermodal units that must be loaded on road vehicles as well as handling time determine the necessary number of handling devices. Due to the difficulties in the road vehicles loading planning, determining the required number of handling equipment becomes an additional problem.

Therefore, in the article for given (random) storage of containers on the storage yard, the time of different variants of handling operations was examined. The analyzed variants include the road vehicle presence/absence in the terminal as well as the number of cranes necessary to perform all the operations at a given daily shift.

Based on the above, we specified 2 variants regarding road vehicle presence/absence on the terminal:

Variant 1. Not all the road vehicles wait for container loading (they did not arrive yet) in the terminal parking lot. It was assumed that the crane operator provides the service of vehicles that are present and ready for loading. It was also assumed that the road vehicle arrival at the terminal is given by the Erlang probability distribution (shape parameter $k = 3$ and scale parameter $\theta = 2$).

Variant 2. All the road vehicles wait for container loading in the terminal parking lot. The crane operator picking up containers from the list of containers to be taken to final customers calls the waiting road vehicle to load the container

In addition to the above variants, it was also assumed that the handling operations could be performed by different number of cranes. Hence, the following variants of the number of cranes used were adopted:

- Variant 1 – 1 crane;
- Variant 2 – 2 cranes;
- Variant 3 – 3 cranes;
- Variant 4 – 5 cranes.

Based on the above variants (2 variants of road vehicle presence, 4 variants of crane numbers) we achieved a compilation of 8 possible research variants. These variants are presented in Table 1.

With the use of FlexSim simulation software the handling operation times, number of operations per crane as well as the

Table 1
Variant numbers

Variant	Crane number variant	Road vehicle variant number
V 1	1	1
V 2	1	2
V 3	2	1
V 4	2	2
V 5	3	1
V 6	3	2
V 7	4	1
V 8	4	2

distance covered by cranes were calculated. For the purpose of the research additional assumptions were made:
- ISO 1A, 1B and 1C containers are handled.
- The initial number of containers in the storage yard was 700. The containers planned for handling are stored in three storage blocks according to containers length. Every storage block consists of 4 storage rows. 1A containers are stored in 25 bays, 1B containers are stored in 11 bays, and 1C containers are stored in 34 bays. As a result, there were 319 of 1C containers, 60 of 1B containers and 321 of 1A containers in different storage blocks.
- The Konecranes RTG crane was used for container handling. Crane parameters referring to crane dimensions as well as handling operations speed were included in the simulation model.
- Assumed average container capture time is 15 seconds.
- Assumed average time of container drop on the road vehicle is 25 seconds.
- Numbers assigned to cranes are: C1, C2, C3, C4, C5.
- Road vehicles for loading are placed next to the bay in which the container is located.

A fragment of the analyzed FlexSim simulation model is presented in Fig. 3.

In Fig. 3, 1A containers are marked in blue, 1B containers are marked in red and 1C containers are marked in black.

It was also assumed that:
- In V3 and V4 variants (2 cranes) one crane handles 1C container and the other one handles 1A and 1B containers.
- In V5 and V6 variants (3 cranes) each crane handles only one type of containers.
- In V7 and V8 variants (5 cranes), two cranes were assigned to 1A containers handling. Other two cranes were assigned to 1C containers handling. Only one crane was assigned to 1C containers handling.

Due to the fact that in some variants (variants V1, V3, V5, V7) the absence of road vehicles at the terminal was taken into account (road vehicles arrive at the terminal in accordance with the given Erlang probability distribution), calculations were made for 20 replications. In addition, for the purposes of the research, it was assumed that each replication contains a different (randomly drawn) system of 50 containers of different types intended for loading on road vehicles. The example of a calculation sample is presented in Table 2.

Table 2
Calculation sample

Container number	Container type	Storage place		
		Bay	Level	row
412	1A	22	3	4
293	1A	1	2	3
369	1C	25	1	3
687	1B	6	2	3
248	1A	3	2	2
650	1A	12	2	4
314	1C	32	2	2
221	1B	6	1	2
674	1A	12	3	3
499	1C	16	2	2
472	1C	12	4	2
606	1A	12	3	1
624	1A	19	2	2
526	1A	23	3	1

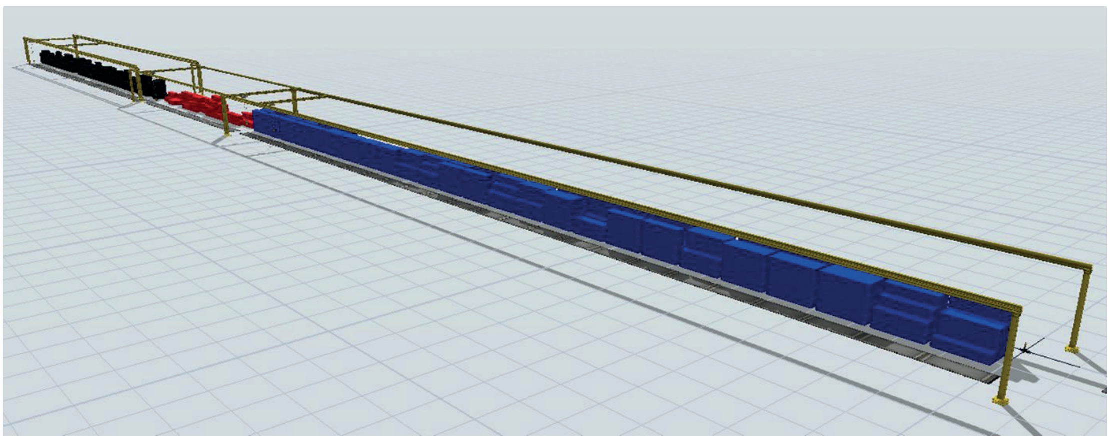


Fig. 3. Simulation model

Table 2

Container number	Container type	Storage place		
		Bay	Level	row
170	1A	20	1	1
94	1A	7	1	1
532	1A	16	4	1
281	1A	5	1	2
530	1A	19	4	4
576	1B	6	2	3
491	1A	11	2	3
41	1B	4	1	3
296	1A	25	3	4
328	1C	14	4	1
635	1B	3	2	4
527	1B	7	2	2
161	1C	16	1	3
387	1C	5	1	1
688	1A	6	2	1
175	1A	23	2	2
477	1C	20	2	3
457	1A	10	2	2
434	1C	28	3	2
216	1C	8	2	1
683	1B	10	2	1
441	1C	7	2	2
408	1A	18	3	3
448	1A	15	2	1
675	1A	1	4	1
95	1C	26	3	2
164	1A	17	3	3
1	1A	19	1	4
665	1A	11	4	3
693	1B	6	3	2
619	1C	33	4	3
672	1A	11	3	1
172	1C	3	2	2
416	1A	22	1	1
253	1A	10	1	2
680	1A	6	4	2

As a result of simulation research, the following is depicted in the figures:
– Distance covered by cranes (Fig. 4);
– Cranes working time (Fig. 5);
– Number of operations (Fig. 6);
– Number of operations per hour (Fig. 7).

In addition, for every variant, the following characteristics are presented (Fig. 8):
– Average working time of all cranes;
– Average number of operations performed by all cranes;
– Average number of operations per hour for all cranes.

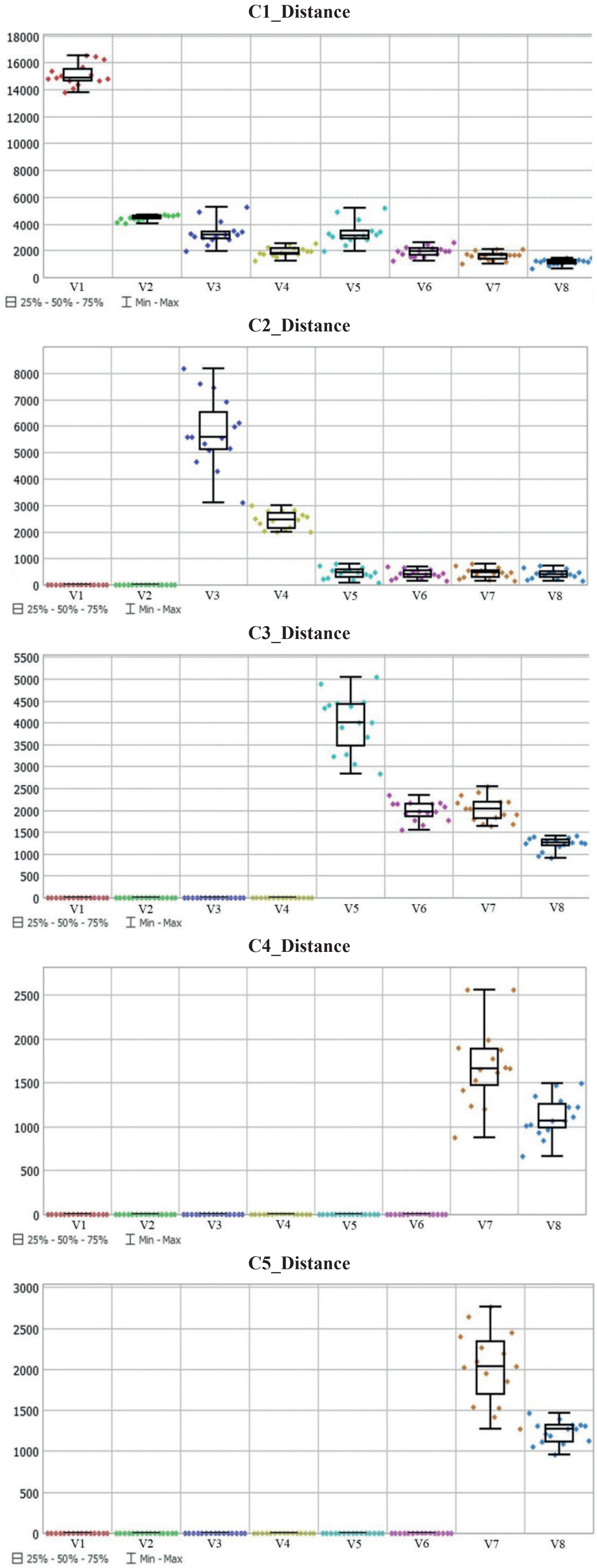


Fig. 4. Distance covered by cranes in variants V1–V8 (in meters)

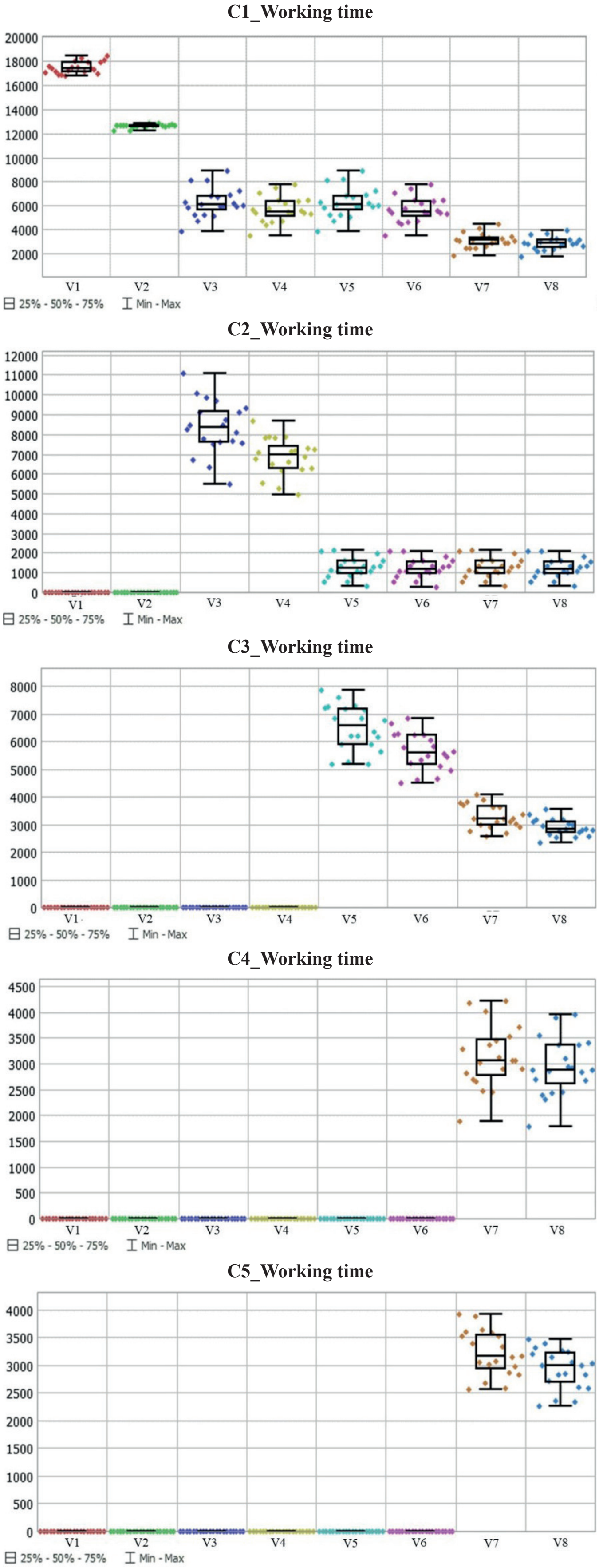


Fig. 5. Cranes' working time in variants V1–V8 (in seconds)

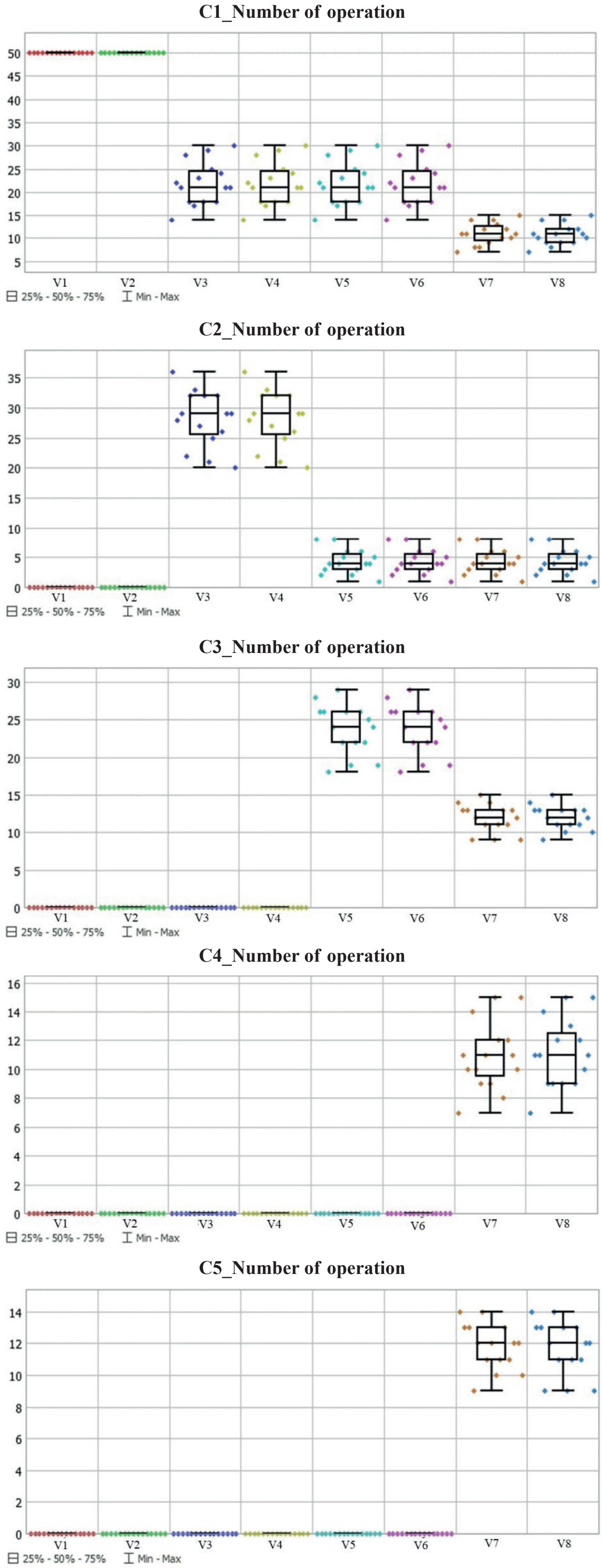


Fig. 6. Number of operations (number of handeled containers) in variants V1–V8

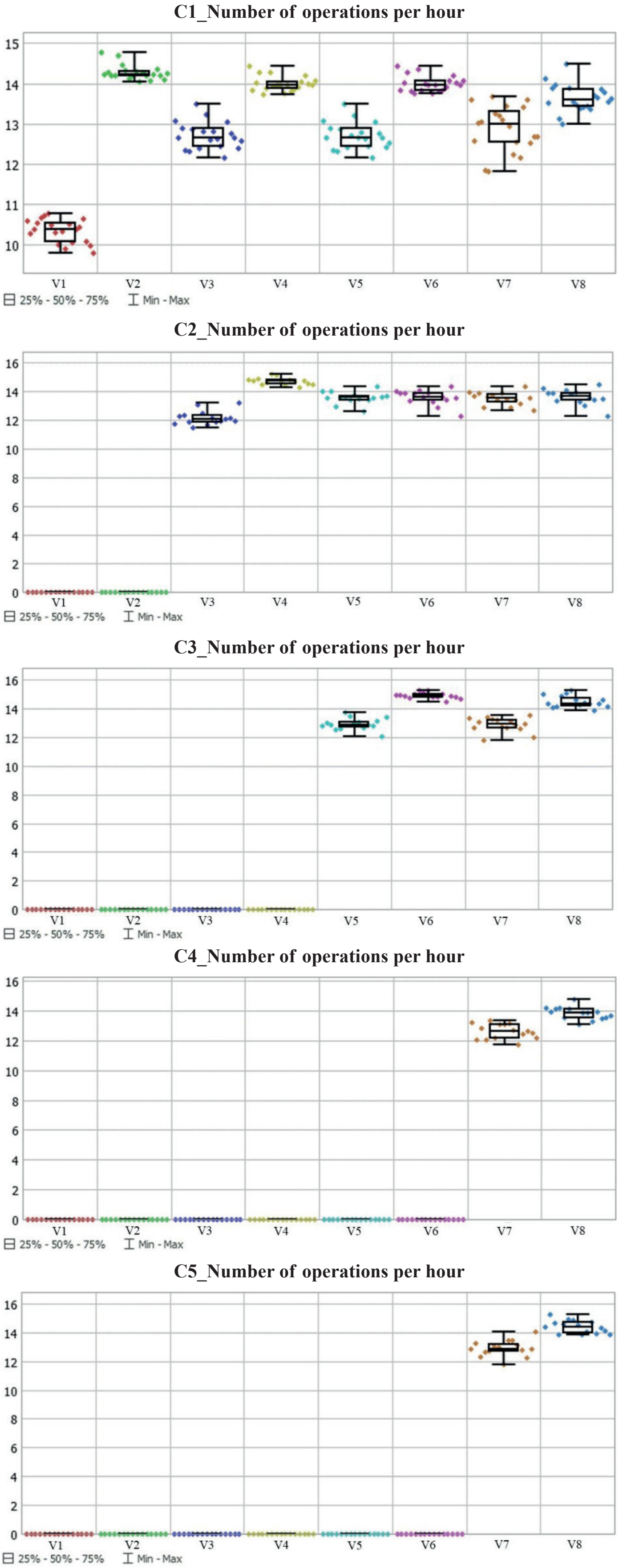
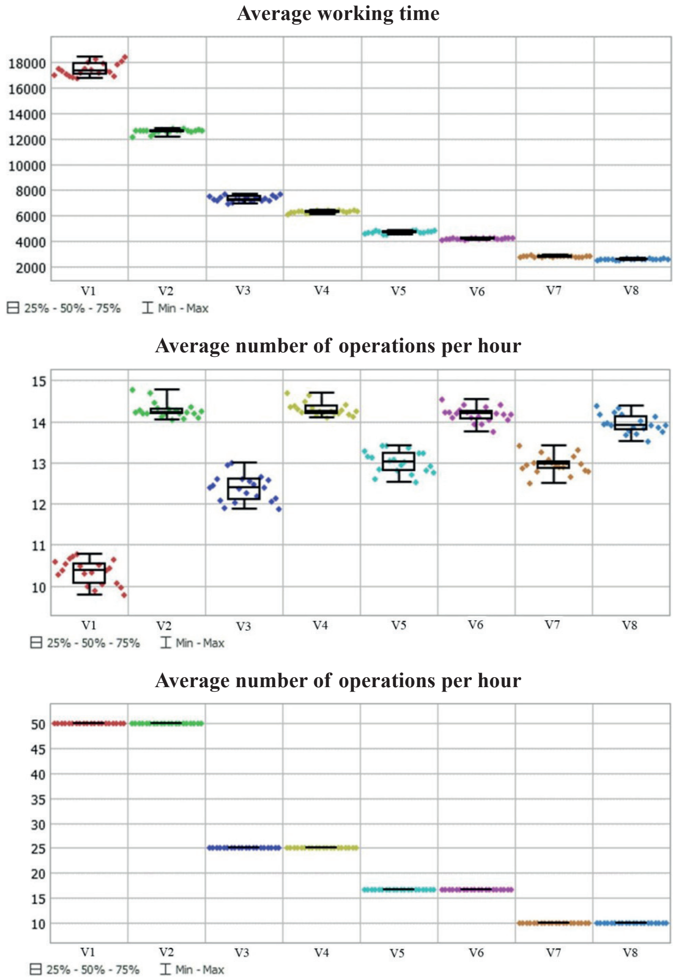


Fig. 7. Number of operations per hour in variants V1–V8



C1–C5 – Cranes numbers; W1–W8 – Variants numbers

Fig. 8. Calculations results in variants V1–V8

The cranes distance in Fig. 4 is presented in meters. It is calculated based on the distance covered by crane gantry and a crane trolley. Lack of results for the C2 crane in variants V1 and V2 is caused by the fact that the crane with this number appears in variants V3–V8 in accordance with previously adopted assumptions. The same is true for cranes with next numbers (e.g. the C3 crane is only available in variant V5).

The distance covered by cranes (Fig. 4) influences their working time. The crane working time includes container pick up from the storage yard as well as its drop on the road vehicle. The dispersion of individual results is caused because:

- Containers for loading are drawn randomly.
- Road vehicles are coming to the terminal randomly in variants V1, V3, V5, V7.

The number of operations (Fig. 6) indicates the number of containers handled by individual cranes in relation: storage yard – road vehicle. An unlimited time has been assumed for the handling, which means that the C1 crane in variants V1 and V2 will service all the 50 containers.

Characteristics regarding the number of operations (see Fig. 7) indicate the number of containers handled by individual cranes in the relation between storage yard and road vehicle within one hour. This is the basic characteristics of crane performance, considered at the stage of equipment selection during intermodal terminal design.

To facilitate the comparison of the analyzed variants, Fig. 8 additionally contains a summary of the average values of characteristics regarding crane operating time and the number of container operations per crane.

From the managers' point of view, a better reflection of the importance of the problem is its quantitative dimension expressed in the form of cost. Therefore, calculations of energy/fuel consumption, costs and pollutant emissions were presented. For the calculation example, crane data available in the manufacturer's catalog was used [61]. The crane consumption was assumed to be 21 l/h for diesel, 10 l/h for hybrid and 50 kWh per hour for the electric crane. For the calculation of energy costs, a price of EUR 0.95/l for diesel and EUR 0.13/kWh was adopted. The CO_2 emissions were assumed as 2.65 kg/l for diesel or hybrid and 0.52 kg/kWH for electric cranes [62]. Based on the above assumptions, consumption, costs, and CO_2 emissions were estimated for each variant (Table 3).

The results were obtained for the plan in which 50 containers are being handled. For large terminals, this number may exceed 1000 TEU/day. Proper scheduling of vehicles that are loading will significantly reduce operation time, and thus energy consumption, costs, and CO_2 emissions. Regarding this issue, it should be noted that the number of cranes in the case of random arrival (V1 vs V7) significantly reduces the total energy costs, while for a well-developed plan the impact is minimal (and even increases the costs compared to variants V2 and V8).

6. Summary

Analysis of the above characteristics for the selection of the number of necessary cranes indicates that for a given number of containers (50 containers), the largest difference in the cranes working time occurs between the variant with one crane and the variant with two cranes. Although better results than in the version with two cranes are obtained for variants with a greater number of cranes, but the differences in these results are small. Even smaller differences between the variants with more than one cranes were obtained for the characteristics relating to the number of container operations performed per hour. This applies especially when the vehicles were waiting for loading at the terminal. In this case, from the point of view of crane number selection, their purchase and maintenance costs, the rational solution are variants V3 and V4.

The analysis of the obtained results was conducted from the point of view of the availability of road vehicles at the terminal and the necessary number of cranes. The analysis of characteristics presented in Figs. 4–8 shows that the average crane working time in variants assuming that road vehicles are ready for loading is much shorter than in the variants were vehicles are randomly available. This difference decreases as the number of cranes increases. This is because the crane does not handle the containers one by one according to the loading list (assuming that the containers on this list are sorted by the distance between the two successive containers), but it does handle containers according to the order of arrival of road vehicles. Similar differences can be noticed for the number of containers handled per hour

Based on the simulation research, a hypothesis can be formulated: for a large number of cranes and in the case of low utilization of transshipment capacity, the impact of the vehicle arrival planning (arranged schedule or random arrival) has a low impact on operating costs. Alternatively, for many services and a high rate of utilization of transshipment capacity, the differences are significant.

Further research will include verification of the hypothesis for various variants of terminal design and vehicle service strategies. However, based on the performed simulation research, it should be stated that when in planning the work of the land terminal, in which the number of cranes is usually small, it is important to schedule vehicles for loading properly. This can bring significant savings as well as less environmental pollution (for this research, for a diesel gantry crane at 2 shifts and 250 working days, savings are around 20,000 EUR/year and 51,800 kg CO_2).

Table 3
Total energy consumption, cost and CO_2 emission for variants

Variant	Average working time for cranes (s) – mean (90% Confidence)	Total energy consumption/cost/CO_2 emission								
		diesel crane			hybrid crane			electric crane		
		Liter	EUR	kg	Liter	EUR	kg	Liter	EUR	kg
V1	17410 (1 crane)	101.56	96.48	269.13	48.36	45.94	128.16	241.81	31.43	125.74
V2	12623 (1 crane)	73.63	69.95	195.13	35.06	33.31	92.92	175.32	22.79	91.17
V3	7318 (2 cranes)	85.38	81.11	226.25	40.66	38.62	107.74	203.28	26.43	105.70
V4	6280 (2 cranes)	73.27	69.60	194.16	34.89	33.14	92.46	174.44	22.68	90.71
V5	4670 (3 cranes)	81.73	77.64	216.57	38.92	36.97	103.13	194.58	25.30	101.18
V6	4175 (3 cranes)	73.06	69.41	193.62	34.79	33.05	92.20	173.96	22.61	90.46
V7	2794 (5 cranes)	81.49	77.42	215.95	38.81	36.87	102.83	194.03	25.22	100.89
V8	2568 (5 cranes)	74.90	71.16	198.49	35.67	33.88	94.52	178.33	23.18	92.73

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