Multi-agent optimization of the intermodal terminal main parameters by using AnyLogic simulation platform: Case study on the Ningbo-Zhoushan Port

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A B S T R A C T

Due to numerous uncertainties such as bad weather conditions, frequent changes in the schedules of vessels, breakdowns of equipment, port managers are aiming at providing adaptive and flexible strategic planning of their facilities, especially intermodal terminals. In this research, we investigate a two-stage optimization of intermodal terminals main parameters via using AnyLogic simulation platform. We have developed a set of hybrid simulation models to optimize the main parameters of intermodal terminals which are also called dry ports. To make an express evaluation of the preliminary implementation of dry ports, we have developed an agent-based system dynamics simulation model to achieve the stable state of the main parameters of intermodal terminals. To clarify the obtained averaged benefits of the main dry ports parameters while the port managers make key decisions on the investments into implementation of intermodal terminals, we have developed an agent-based discrete-event simulation model of a seaport – a dry port system. We show that the combination of the agent-based modeling with other simulation approaches simplifies the process of designing simulation models and increases their visibility. The developed set of models allows us to compute the balanced values of the parameters, while an effective operation of a seaport – intermodal terminal system is achieved. On the basis of the provided case study on one of the busiest ports in China, we prove the adequacy and validity of the developed simulation models. Due to the lack of systematic approach to optimization of the main parameters of intermodal terminals in logistic industry, our findings set herein could improve the decision-making process related to the selection of strategic facility planning in the field of intermodal terminals.

1. Introduction

Nowadays, one of the global trends is the increase in the number of containerized cargoes in the world and the volume of container shipping in the world transport system ("UNCTAD. Review of Maritime Transport 2019"). However, there has been no increase in container volume at major ports all over the world in the last five years ("World Shipping Council. Top 50 world container ports"). The location of ports in residential zones constrains its development and growth of container volumes (Muravev, Rakhmangulov, Hu, & Zhou, 2019). Consequently, port managers have faced the problem of expanding the port territories around maritime terminals.

Undoubtedly, in order to increase the throughput and handling capacities of maritime container terminals, they have to jointly operate with intermodal terminals which are also called dry ports (Cullinane, Bergqvist, & Wilsimsmeier, 2012; Jeevan, Chen, & Cahoon, 2017; Roso, Woxenius, & Lumsden, 2009). A dry port is an inland intermodal terminal directly connected to a seaport, with high capacity traffic modes, preferably rail, where customers can leave and/or collect their goods in intermodal loading units, as if directly to the seaport (Roso et al., 2009). Such kinds of terminals as the elements of supply chains (Andersson & Roso, 2016) also contribute to their development through enhancing the outcomes of cost, responsiveness, security, environmental performance, resilience, and innovation in logistic networks (Khaslavskaya & Roso, 2019). However, the regular changes in the schedules of container vessels and trucks arrival times due to increased traffic volume lead to an increase in container capacity of vessels, customs clearance, and other disruptions, such as breakdowns of equipment and bad weather conditions, contribute to the dynamic
development of port facilities (Jeevan & Roso, 2019; Loh & Thai, 2015; Muravev, Rakhmangulov et al., 2019) and supply chains as a whole (Ivanov, Sokolov, & Kaesche, 2011; Ivanov, Das, & Choi, 2018). It means that these facilities have been facing challenges in operations, such as difficulty in meeting different stakeholder objectives, constraints of the storage capacity and limited availability of transportation modes. Furthermore, the external social and environmental factors constrain the development of logistics facilities. For example, from the social perspective, the negative dynamics of the number of people inhabiting the potential location of the intermodal terminal makes the wages of terminal workers lower because of the reduced demand for job offers. From the environmental perspective, the physical expansion of the container yards could be limited by the conservation areas and irrational land use in the area of the potential dry port location (Muravev & Rakhmangulov, 2016). In other words, these factors affect the parameters of the intermodal terminals.

This complexity, dynamics and the systematic consideration of social and environmental factors call for adaptive and flexible planning in intermodal terminals, i.e. obtaining the optimal values of their parameters. In reality, strategic facility planning (SFP), especially in port management, lies in numerous activities. These activities come into the sphere of the port managers’ responsibility, causing frequent lapses into a reactive mode in order to respond to all the requests, orders, regulations, deadlines and demands of the organization. Port managers know that the need to become more proactive and strategic is important, but finding the time to devote to strategic planning is often a struggle. Strategic planning of logistic facilities is a process that can lead to better, more proactive delivery of services from a port management organization to its stakeholders. Generally, the SFP performance in case of port management is measured by financial indicators, such as general and operational costs of the project, Return on Investment (ROI), Net Present Value (NPV) and Discounted Payback Period (DPP) (Dang & Yeo, 2017; Elentably, 2015; Taneja, Ligteringen, & Walker, 2012). Therefore, the central terminal management problem is to optimize the long term physical and technical parameters of intermodal terminals and the parameters of traffic flows. These optimal values of parameters are characterized by low investments and sustainable social, economic and environmental impacts. In order to evaluate the operational performance of facilities, scholars in the field of logistics and transportation have been mainly applying numerous traditional deterministic methods such as integer linear programming (Li, Tian, Cao, & Ding, 2008) and mixed linear programming (Daham, Yang, & Warnes, 2017), genetic algorithm (Razzazi, Safaei, & Javadian, 2009; Ng, Mak, & Zhang, 2007; Said & El-Horbati, 2015), etc.

However, these methods could not consider systematically the rapid dynamic development of logistic facilities and the impact of the external factors on the parameters of the intermodal terminals. One of the effective ways to investigate this impact is a combination of analytical and simulation models, which provide port managers with clear insights into solving such problems as bottlenecks in the system, duration of the long-term life cycle, etc.

This research is twofold. Firstly, in order to provide the express assessment of the dry port construction project, we investigate the systemic analysis of the impact of various external factors on the main parameters of an intermodal terminal. Specifically, we have developed an agent-based system dynamics simulation model (ABSDS model), which optimizes the averaged values of main dry port parameters. Secondly, in order to provide an appropriate detailed assessment of the project, we have developed an agent-based discrete event simulation model (ABDES model) of a seaport – dry port system. Basically, this model ensures the detailed estimation of financial indicators of a seaport – dry port system with the obtained optimal values of the intermodal terminal main parameters.

The rest of the article is organized as follows. Section 2 reviews the existing and relevant literature. Section 3 proposes the framework of a set of combined simulation models in the AnyLogic simulation platform to optimize the main parameters of intermodal terminals. Section 4 presents the case study on validation benefits, results of the optimized dry port main parameters and its financial performance indicators. Section 5 explores theoretical and managerial contributions, limitations and future research perspectives of the developed methodology. In Section 6 conclusions are discussed.

2. State of the art

2.1. Strategic facility planning

Our study is based on a review of three methodological aspects. Firstly, we greatly benefited from the literature on strategic facility planning related to container terminals. Secondly, we provide a review of studies dedicated to the combination of the agent-based and system dynamics simulation approaches in the field of terminal planning. Finally, studies on the microsimulation port facilities operation pointed out the direction in the development of the simulation model in our study.

The trend in today’s global market and supply chain management requires adequate planning of sustainable logistic processes in order to achieve successful business strategies, specifically in freight terminals (Mehrooif, 2019; Tadić, Krsić, Roso, & Brnjac, 2019). The first reports on terminal planning and operations were presented in the UNCTAD handbooks and Port Planning Development in 1987 (Frankel, 1987). Then, in 2011, Böse & Jungen completed the state of the art of the research in container terminals design, management, and planning. Hence, it motivated scholars to study the terminal planning from different perspectives such as facility location problem, routing problem, travelling salesman problem and management of terminal operations (Böse, 2011).

Tuzkaya et al. studied strategic planning for the multimodal transportation systems in Turkey to select the most feasible transportation mode between seaports and multimodal terminals by applying a combination of the analytical network process and multilevel programming technique. They provided a comparison between different transportation modes by using the following variables such as unloading and loading costs, waiting costs (Tuzkaya, Onut, & Tuzkaya, 2014), Braeckers et al. optimized drayage operations in the service area of intermodal terminals and formulated it as an asymmetric multiple vehicle Traveling Salesman Problem with Time Windows, which has been solved by hybrid deterministic annealing and tabu search algorithm (Braeckers, Caris, & Janssens, 2014). Pamucar et al. selected the optimal location of the city logistic terminal in Belgrade by using graph method and neural networks and applied the following variables: costs of logistic distributors, environmental parameters, sociological parameters (Pamučar, Vasin, Atanasković, & Miličić, 2016). Teye et al. studied the facility location problem in case of locating urban and regional container terminals by means of entropy maximization with linear programming. The authors used such variables as fixed costs of an intermodal terminal, its handling capacity, the quantity of cargo, demand (Teye, Bell, & Bliemer, 2017). Heggen et al. investigated the impact of long-haul routes and fixed drayage tasks associated with intermodal terminals by using a large neighborhood search method (Heggen, Molenbruch, Caris, & Braeckers, 2019). Abubakar et al. studied the prediction of knowledge hiding behavior of employees to improve the knowledge management at different types of industries (Abubakar, Behravesh, Rezapouraghdam, & Yıldız, 2019). Authors applied artificial neural networks with partial least squares regression to obtain the results of the predictor variables.

On the basis of the provided review, we can conclude that there has been a trend to solve the problems of operations research in the field of terminal planning by combining different techniques. However, there are no studies that cover all the problems at the same time. Basically, the authors solve one or two problems simultaneously.

2.2. System dynamics agent-based simulation modeling

The structure of intermodal terminals is complicated since a large number of factors such as increased traffic volume, breakdowns of
equipment and bad weather conditions together affect the different parameters of the terminals (Felício, Caldeirinha, & Dionísio, 2015). One of the efficient methods of investigating this negative impact (disruptions) is the system dynamics (SD) method developed by Forrester (Forrester, 2007). This method considers all the factors holistically and determines the most critical factors that govern the main characteristics of the system during its designed life (Mallick & Solaimanian, 2015). Soares et al. developed the system dynamics model to predict the capacity of the container terminal and its behavior with demand and productivity (Soares & Neto, 2016). However, if researchers aim at additional variables, labor inputs to design the SD model will increase. Moreover, the differences between the theoretical and practical implementation of the simulation model will potentially occur. Yang & Tong investigated the SD simulation model of logistic enterprise core competence by studying the following factors: making capacity, technological innovation, and operational capability, etc. Nevertheless, the proposed method could not provide the scalability of the model and accurate result that is important when the main investment decisions are being made (Yang & Tong, 2017). Mamatok et al. developed a system dynamics model for CO₂ mitigation strategies at a container seaport and studied the impact of such variables as emission factors of the vehicle, cargo handling equipment, and ocean-going vessels, etc. Nevertheless, a causal loop diagram presented in the study with a huge number of studied parameters and factors leads to the loss of the SD model visibility and makes the study difficult to understand (Mamatok, Huang, Jin, & Cheng, 2019).

Traditionally, the system dynamics approach has been applied in the field of transportation and supply chain management at the macro-level in order to analyze the bullwhip effect of external factors influencing different parameters.

Currently, the modern approach to solving the problems of complex systems is the modeling of the multi-agent system (Chargui, El fallahi, Reghioui, & Zouadi, 2019; Dlugosch, Brandt, & Neumann, 2020; Ivanov, 2017a). This approach provides a clear understanding of how the parameters of the system are interrelated with each other (Liang & Huang, 2002). The main distinctive feature is that the agents could be potentially represented as the main parameters of logistic terminals. Moreover, designing the relations between them is not laborious (Qiao, Shan, Zhang, & Liu, 2019). However, to the best of our knowledge, there are few studies related to the combination of agent-based and system dynamics modeling in the field of determining the optimal values of the container terminals parameters.

2.3. Discrete-event agent-based simulation modeling

The situation in the field of hybrid agent-based discrete-event simulation modeling of the operation of logistic facilities cardinally differs from a combination of system dynamics and agent-based modeling. The combination of discrete-event and agent-based simulation approaches is highly suitable for distributed problem solving as they offer the possibility to divide the main task into small subtasks (Smith & Davis, 1981). One of the first papers dedicated to a combination of two approaches in the field of logistics and transportation was published by Gambardella et al. in 2002 (Gambardella, Rizzoli, & Funk, 2016). The authors developed the agent-based discrete-event simulation model of the flow of intermodal terminal units among the inland intermodal terminals using MODSIM III simulation platform. They modelled the operation of the intermodal terminal with different modes of transport such as road and rail. However, the authors have not considered a probability distribution for the random variable to simulate different operations such as the arrival of vehicle, loading & unloading operations, etc. It could potentially reduce the accuracy of the results.

Onggo & Karatas constructed the agent-based model of maritime search and rescue and patrol operations (Onggo & Karatas, 2015). The model of the MASSIM simulation platform consists of two agents such as searcher and target. The main objective of the searcher is to detect the target. According to their behavior, targets can be classified into three groups: a cooperative target that wishes to be detected by the searcher (e.g. the victims in a search and rescue operation), a non-cooperative or evading target that is willing to hide or escape from the searcher (e.g. a refugee trying to reach his/her destination without being detected by the coast guard), and a non-cooperative target that wishes to be as close as possible to the searcher without being detected (e.g. a hostile submarine trying to approach surface ships as close as its effective torpedo range). Nevertheless, the scale of the proposed model is closely designed at meso level which is not correlated with microsimulation that is associated with agent-based discrete-event simulation.

Abourraja et al. developed a multi-agent simulation model for rail–rail transshipment yard at Le Havre Port to solve the problem of gantry crane scheduling by using the AnyLogic simulation platform (Abourraja et al., 2017). The authors proposed such agents as operational planner agent who takes short-time planning decisions on incoming freight trains, determining the resource allocation and handling or departure operations with freight trains; a tactical planner agent which schedules intra-port container transfer activities (medium-time planning decisions) by determining the required number of shuttles and considering containers characteristics (such as size, type, origin, target terminal and date of arrival at maritime terminals; transport service provider agent, who creates long freight trains and plans their arrival and departure dates from multimodal terminal by representing rail transportation actors and coordinating container routing to and from Le Havre seaport over its hinterland. Still, the authors have not represented the vehicles and handling equipment as the agents, which could simplify the visibility of the developed model and interaction between agents. Furthermore, the authors have not represented the process flowcharts developed in the internal environment of the agents, since they applied Agent Library, State Chart, Rail Library and Process Modeling Library of the AnyLogic simulation platform.

Frazzon et al. developed a smart port-hinterland integration concept based on the application of a simulation DES model to analyze the port processes and micro-simulation technique to investigate the behavior of urban road networks or other congested sites (Frazzon et al., 2019). The authors used two software: Aimsun and SimPy. The Aimsun hybrid simulator provided the macroscopic modeling and simulation of the travel demand was implemented to identify the bottlenecks of the road network. The SimPy discrete-event simulation software was applied to analyze numerically the queues in the gatehouses of the Brazilian ports. However, the application of two software is time-consuming, since the authors solved technological problems of the port operations. Furthermore, it loses the visibility of the developed simulation models.

Collectively these studies have advanced agent-based discrete event modeling of the logistic facilities operation. However, they cannot adequately capture certain aspects in the real-world transportation environment, for example, operation uncertainty and disturbances, which are reducing the applicability of these methodologies. Furthermore, these studies are dedicated to solving separate issues such as operations management, scheduling, and facility location. Finally, most authors applied different simulation platforms instead of AnyLogic simulation which consists of three simulation paradigms such as agent-based, system dynamics and discrete event simulation.

2.4. AnyLogic in facility planning problems

AnyLogic simulation platform has proved to be a useful tool for solving facility planning problems, specifically in the Supply Chains (SC). Rozhkov et al. applied AnyLogic simulation platform to compare SC performance impacts with regard to coordinated and non-coordinated ordering and production control policies. The authors applied agent-based discrete event simulation with parametrical optimization of the costs allocation in the Supply Chain by OptQuest optimizer integrated into AnyLogic (Ivanov & Rozhkov, 2017). Gianessello et al. studied six-echelon closed-loop supply chain of Tesla from the perspective of its resilience by using disruption and recovery scenarios. The authors
applied anyLogistix simulation software which is similar in functionality to AnyLogic simulation platform (Gianesello, Ivanov, & Battini, 2017). Ivanov analyzed the SC design and production-ordering systems in the recovery and post-disruption periods. The author investigated the change of key financial, customer, and operational performance in SC by using the anyLogistix software. This software is developed by AnyLogic company and lies in Network Optimization by using integrated CPLEX optimizer. The anyLogistix software also provides agent-based, system dynamics and discrete-event simulation (Ivanov, 2017b). This software also includes stochastic, dynamic, variation, and comparison experiments related to facility location planning, multi-stage and multi-period SC design and planning, inventory control, transportation control, and sourcing analysis (Ivanov, 2019a, 2019b).

3. Multi-agent optimization of the intermodal terminals main parameters

3.1. Methodology to develop the seaport – dry port system

The selection of the main dry ports main parameters is presented in (Muravev, Rakhmangulov et al., 2019). The following main parameters were selected: (λ) intensity of traffic flows (TEU/day); (Kir) coefficient of variation of traffic flows; (L) distance between seaport and dry port (km); (Ttr) throughput of transport communications (pairs of trains/day); (Eo) the location of the dry port, characterized by the volume of grading operations at the potential area of dry port location (score); (V) storage capacity of the dry port (TEU); (n) throughput capacity of the dry port (TEU/day); (Ed) environmental parameter considered in the dry port area location (score); (Gc) general costs of the dry port construction (mln USD); (Oc) operational costs of the seaport – dry port system (thous USD).

The selected main parameters are interrelated between each other through linear dependences and form the system developed in the study (Muravev, Rakhmangulov et al., 2019). The methodology to optimize the main dry ports parameters consists of 12 stages presented in Fig. 1.

The most disturbing parameter in the studied seaport – dry port system is the change of intensity of incoming freight traffic flows, determined by the coefficient of the irregularity of these flows. Hence, in order to obtain the optimal values of the main intermodal terminals parameters, the proposed system of the parameters should achieve a stable state dynamically. Several factors could unbalance the system of the main intermodal terminals parameters. Firstly, since we propose interaction between the selected parameters through linear direct and inverse dependencies, the incorrect selection of dependency type between a pair of parameters could unbalance the system. Secondly, the irrational selection of the main intermodal terminals parameters could destabilize the system due to the inappropriate number of inverse dependencies between parameters. Consequently, it prevents the development of the self-regulatory system of the main intermodal terminals parameters. Finally, uncalibrated coefficients of the linear functional dependences between the parameters could unbalance the system.

In order to overcome these challenges, we propose to design a simulation model presented in the next section and based on the combination of agent-based and system dynamics approaches in the simulation platform AnyLogic 8.5.1.

3.2. Multi-agent system dynamics simulation model of the main dry ports parameters

The application of the hybrid simulation model has several benefits. Firstly, the agent-based approach allows us to scale the model in order to study the system of the main intermodal terminals parameters at the micro-level. Moreover, this approach is less time-consuming and makes the developed model universal. It becomes crucial if we need to increase the number of studied parameters and factors affecting them in a system. Secondly, the system dynamics approach is used to investigate the change of the main parameter of the intermodal terminals, depending on the change of other parameters. Undoubtedly, we have an alternative way to develop the system dynamics of the dry ports main parameters. This alternative lies in deriving the differential equations system (analytical approach) or system dynamics (simulation modeling method). However, none of them are able to scale the system that is being crucial for micro-level cases. This situation would potentially increase labor and it is a time-consuming procedure to study the intermodal ports parameters. The key originality of the developed hybrid model is the creation of the agents’ population, which represents the main parameters of the intermodal terminal with the same structure in the agent’s environment presented in Fig. 2. The validity of the proposed system dynamics model of the main dry ports parameters has been proved in the study (Muravev, Hu, Rakhmangulov, & Dai, 2019).

Moreover, we recommend the simplified way of agents’ interaction based on transferring the messages between each other and their further processing. In other words, we have also developed the agent Message which has the following variables such as parameterName, parameterNumber, parameterIncrease, and parameterDecrease.

The operation of the hybrid ABSDS model is based on 4 stages presented in Fig. 3:

Step 1. Calculate the functional interrelations between main parameters of the dry port with the developed system of the main dry port’s parameters.

- Step 2. Develop multi-agent system dynamics simulation model of the main dry ports’ parameters with further adjustment of coefficients in linear functional interrelations between the main dry port’s parameters.

- Step 3. Apply the obtained optimal coefficients of linear functional interrelations as constraints of the objective function (minimizing the NPS) for determining the optimal average values of the main parameters by CPLEX optimizer (express evaluation of the project).

- Step 4. Analyze the master plan of the existing seaport, its variants, the scheme of both rail tracks at port railway station and special tracks, port operations.

- Step 5. Collect the data on the duration of different port operations, traffic volumes including container vessels, trains and ferries.

- Step 6. Calculate the existing and predicting values of intensity and irregularity of traffic volumes.

- Step 7. Develop the multi-agent discrete-event simulation model of the seaport-dry port system and carry out the experiments on the estimation of the maximum throughput of the seaport by applying the data on intensity (J) and irregularity (Ω) of traffic volumes.

- Step 8. Make the decision on the implementation of the dry port, if the seaport is unable to handle the traffic volumes with feasible operational costs.

- Step 9. Select the scenarios of the dry port’s construction and determining for each one the values of the main parameters: distance (L) between seaport and dry port; storage capacity (V) of the dry port; general costs (Gc) for construction of the dry port.

- Step 10. Extend the developed multi-agent discrete-event simulation model by adding the standardized block, imitating the operation of the dry port in interaction between seaport port and intermodal terminal.

- Step 11. Set up the objective function (price cost of container handling) and constraints (obtained optimal values of the main parameters, Step 3) in the optimizer OptQuest, which is integrated into the AnyLogic software.

- Step 12. Determine optimal specified values of the main dry port’s parameters (L, V, Fc, V, n, K, Gc, Gw, D) for each scenario of the port infrastructure’s development by carrying out the experiments with the developed simulation model of seaport-dry port system with different values of the intensity (J) and irregularity (Ω) of traffic volumes.

Fig. 1. The methodology of developing the seaport – dry port system.
1) running simulation with the application of Database in the external Excel-file;
2) generation and transferring messages on changing the value of the agent (the main parameter of a dry port);
3) receiving and processing these messages;
4) the algorithm to adjust the values of coefficients of linear functional dependences between the parameters

The fourth algorithm was developed in order to achieve the sustainability of the system of the intermodal terminals main parameters during the simulation period.

One of the key distinguishing features of the developed algorithm presented in Fig. 3.1 is its universality, which lies in its application to the study of different complicated systems, further identification of parameters with the most destabilizing impact on the system and the final adjustment of their coefficients. Another feature of the developed algorithm is providing a temporary adaptation period to the agents-parameters after saving the selected coefficient of functional dependence into an external Excel-file. This is necessary to determine the stability of the system of the main intermodal parameters, which have 100 established connections between each other.

Since the model provides the calibrated values of the coefficients in linear functional dependences, these values are going to be applied in the optimization of averaged main intermodal terminals parameters.

The objective function is the criterion of maximum Net Present Value (NPV) determined by the following formula:

$$NPV = \sum_{k=1}^{N} \left( \frac{TA_k}{A} - (O_{k,1} + G_{k,1}) \right) \eta_k \rightarrow \max$$

(1)

The value of annual costs would result in the indicators of operational costs $O_k$ and general costs $G_k$ obtained in one model year. Consequently, $O_{k,1} = O_k/A$, $G_{k,1} = G_k/A$, where $A = T/365$, and $T/365$ is the duration of the modeled period (estimated period) in months, $O_k$ and $G_k$ are the sums of total modeling period. $\lambda$ is the daily number of containers handled in the intermodal terminal; $\eta_k$ is the value of the current tariff during the $k$-th year; $\eta_k$ is the discount coefficient.

The constraint of the optimization model is presented in the following formula:

$$x_{j_{\min}} \leq \sum_{i=1}^{j} s_{ij} x_i \leq x_{j_{\max}}$$

$$...$$

$$j \leq N$$

(2)

where $x_{j_{\min}}, x_{j_{\max}}$ are the estimated bounds of the main parameters of the dry port. If the impact of the parameter $x_i$ on the parameter $x_j$ is negative, $s_{ij} = -1$, if $i = j$, $s_{ij} = 0$. $s_{ij}$ is the functional linear dependence between parameters $x_i$ and $x_j$.

**Fig. 2.** The example of the universal structure of the agent and its internal environment in the simulation platform AnyLogic 8.5.1.

**Fig. 3.** The pseudocode of the developed ABSDS model of the main dry ports parameters.
3.3. Multi-agent discrete-event microsimulation model of the seaport – dry port system

The main purpose of the ABDES model of the seaport – dry port system lies in obtaining the refined, detailed optimal values of the dry ports main parameters. In other words, different stakeholders, such as port authorities and local governments, could apply these values to further construction of an intermodal terminal. One of the distinctive features of the developed simulation model lies in the lack of need to reconfigure flowcharts, when users change the input parameters of the model. In other words, the application of the universal blocks of the Process Modeling Library of AnyLogic simulation platform in the agents presented in Appendix Table A1 reduces the labor costs of the design simulation model (Cavalcante, Frazzon, Forcellini, & Ivanov, 2019; Muravev, Aksoy, Rakhmangulov, & Aydogdu, 2016).

Thus, we combined the agent-based and discrete-event (process-centric) approaches in order to simulate the operation of different handling equipment, vehicles, and rolling stock, which is being crucial in micro-simulation to identify each unit of the rolling stock or the container. The developed model presented in Fig. 4. Consists of different agents:

- dynamic agents (entities), containing the parameters of containers, container vessels, freight wagons, Fig. 4.1, 4.4, 4.6;
- static agents (handling equipment and facilities), simulating the operation of berths, container yards, cranes, forklifts, container lorries, Fig. 4.2, 4.5;
- controlling agents (dispatching agents), handling the traffic flows as well as the interaction of different agents in the model, Fig. 4.3.

The overall flowchart of the developed ABDES model of the seaport – dry port system is presented in Fig. 5, which represents technological operations performed with the use of the process flowcharts. The duration of technological operations is set up according to normative values estimated in the seaports. The random deviations of various technological operations and the intensity of traffic flows are set up by distribution laws of random variables.

The operation of the developed simulation model is based on the implementation of intermodal transportation. With the arrival of the container vessel, the model checks the available quay, Fig. 4.1. If the quay is occupied, the container vessel stays at the anchorage area of a
Model values of the dry port locations variants. Since the containers are transported to container yards at both seaport and dry port, port operations could be performed. The transportation of containers between the seaport and the dry port is organized by rail, Fig. 4. The unloading of vessels is performed in two ways: direct unloading, container vessel – railway platform; warehouse unloading, container vessel – quay – container lorry, Fig. 4.3. The transportation of containers between the seaport and the dry port is characterized by different general costs. These variants were set up as one-dimensional arrays depending on the values of the investment costs made to develop the distance between the seaport and the dry port, the throughput of transport communications between the two terminals, the topography of the area, the storage capacity and the handling capacity of the dry port, as well as the environmental situation.

In order to estimate the cost price of container handling which is one of the key performance indicators of the seaport – dry port system operation, an example of the internal interface of the optimization experiment in the AnyLogic simulation platform is presented in Fig. 6.

As can be seen from Fig. 6, the varied parameters in optimization are the storage capacity of a dry port, the distance between the seaport and the intermodal terminal, the intensity & irregularity of the traffic flows as well as the variants of the dry ports location which are characterized by different general costs. These variants were set up as one-dimensional arrays depending on the values of the investment costs made to develop the distance between the seaport and the dry port, the throughput of transport communications between the two terminals, the topography of the area, the storage capacity and the handling capacity of the dry port, as well as the environmental situation.

To calculate the variable costs in dynamic variables of AnyLogic simulation platform such as electricity consumption of Ship-to-Shore (SSG) cranes, we propose the following formula: ssgCrane.utilization = number of SSG crates * 200’0.08, where the function ssgCrane.utilization () is the total working time of the SSG cranes (ssgCrane is ResourcePool block of the Process Modeling Library in the AnyLogic simulation platform presented in Appendix Table A1); number of SSG cranes is the variable which displays the total number of cranes; 400 is the power of the electric drives SSG cranes (kW h); 0.08 is price per 1 kW h in US dollars. Furthermore, in order to estimate the dwell time of vehicles and transfer it to penalty costs, we applied the programming code: timeMeasureEnd.dataset.size() \[0 \Rightarrow 0\text{ ?} 0 : \text{timeMeasureEnd.dataset.getX(timeMeasureEnd.dataset.size()-1)/day*90, where timeMeasureEnd is the time counter recording the moment of the vessel’s departure from the port, Appendix Table A1; day equals 1440 (minutes/day); 90 is the demurrage of the container (US dollars/day).}

4. Case study & results

The case study is based on the Ningbo-Zhoushan port located in Zhejiang Province, China and has its own dry port located in Yiwu city. The main purpose of this case is to investigate the bottlenecks and mistakes of the dry port location in China, i.e. validate the actual values of the dry port main parameters in the Yiwu city.

To date, the Ningbo-Zhoushan seaport is one of the busiest maritime terminals in the world, handling approximately 25 mln TEUs annually (Li, Hilmola, & Panova, 2019). Furthermore, this port is an indispensable transshipment hub in the supply chains launched by One Belt One Road Initiative (Zhang, 2019). However, this seaport is now experiencing lengthy delays and queues of vessels at anchorage waiting to enter the terminals for at least seven days. According to comments from the Maersk shipping line, the leading causes of congestions are long stays of containers at the terminal and challenging weather conditions in China. Another reason for such an extreme situation at this Chinese seaport is its limited throughput and storage capacities because of its location in the residential zone (Muravev, Rakhmangulov et al., 2019).

The Ningbo-Zhoushan port has eleven container terminals which

Table 1
Model values of the dry port locations variants.

<table>
<thead>
<tr>
<th>Number of the point</th>
<th>Variant 1, V = 1000 TEU’s</th>
<th>Variant 2, V = 2000 TEU’s</th>
<th>Variant 3, V = 3000 TEU’s</th>
<th>Variant 4, V = 4000 TEU’s</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>27</td>
<td>29.4</td>
<td>26</td>
<td>32.6</td>
</tr>
<tr>
<td>2</td>
<td>23</td>
<td>28.2</td>
<td>22</td>
<td>29.7</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>7</td>
<td>19</td>
<td>22.9</td>
<td>18</td>
<td>22.7</td>
</tr>
</tbody>
</table>
handle container vessels with capacity up to 21,000 TEUs. However, only two terminals jointly operate with the port railway stations, providing railway transportation on the mainline network of the railways. The main container terminal at the Ningbo-Zhoushan port is the Ningbo Bellun Container Terminal (NBCT). According to the data provided by Marine Traffic, the monthly intensity of container vessels' arrivals is up to 10 container vessels with an average capacity of 10400 TEUs. The technical parameters of the NBCT terminal are presented in Table 2.

According to the United Nations Economic and Social Commission for Asia and the Pacific (UNESCAP), the Ningbo-Zhoushan has been jointly operating with 10 dry ports ("UNESCAP. Development of International Dry Port in China," 2019). However, on the basis of the conducted survey with the terminal manager at the NBCT terminal, we identified Yiwu dry port and its main parameters as the bottleneck in the operation of the Ningbo-Zhoushan port.

Yiwu dry port was constructed in 2013. Nowadays, there are three daily trains from this terminal, which is located 185 km away from the sea port where the throughput of transport communications equals 12 pairs of trains daily. Moreover, it has two separated rail hauls for the China Railway Express and the Ningbo-Zhoushan. The Yiwu dry port could simultaneously store 800 TEU and handle 450 TEU daily. Besides two reachstackers, 50 lorries and 25 RTG cranes operate at the terminal. About 25% of the traffic flow between NBCT and the Yiwu dry port is transported by rail. The total investment costs of the project are about 461.35 million US dollars.

The irregularity of traffic flows between the NBCT terminal and the Yiwu intermodal terminal has increased up to 2.2. It means that the disruption of shipments in the system forms the delays of vehicles such as container vessels, trains, etc. One of the reasons for disruptions in the system is the distant location of Yiwu dry port because of the high cost of land. Obviously, such a distant location increases the backorder demand associated with the seaport. This fact involves possible existing heavy weather conditions resulting in the disruption of the traffic flows at the marine terminal.

In order to obtain averaged optimal values of the main parameters of the dry port, we calibrated the coefficients of linear functional dependences between the main parameters of Yiwu dry port by the developed ABSDS model, whose validity has been proved in the study (Muravev, Rakhmangulov et al., 2019). In other words, the simulation model dynamically selected the values of the coefficients during the simulation period of 120 months.

The bounds of the dry port main parameters can be justified by minimum and maximum value. For example, the rail traffic intensity has bounds [100; 300] containers/day, where the minimum value describes the minimum number of containers in a single train and the maximum value lies in the expected maximum number of containers transported by rail to the dry port and is taken from collected data. An example of the modeling results is presented in Fig. 8. The presented figures illustrate that the period of stabilization of the main parameters of Yiwu dry port equals 20 months. The obtained calibrated coefficients are presented in Table 3.

Secondly, since we obtained the calibrated coefficients of linear functional dependences, the optimization of the main parameters should be carried out.

The optimization of the main dry ports parameters is carried out in the integrated development environment IntelliJ IDEA by importing the CPLEX library. The optimal averaged values of the main dry port parameters are presented in Table 4.

The next step of the study lies in carrying out a series of experiments by applying the developed ABDES model to estimate the maximum throughput of the existing NBCT terminal – Yiwu dry port system and proposed NBCT terminal – optimal dry port system taking into account obtained optimal averaged values of the main dry ports parameters.

The following ranges of the intensity of traffic flows have been applied: container vessels [5;15] units/month with their average capacity of 10400 TEU’s, freight wagons [100;500] railcars/day. The coefficient of the irregularity of the traffic flows is ranged in [1.3;2.2]. The normative value of the time which a wagon spends on the private railway tracks of the system equals 8.5 hours, while its value of the time which a container spends in the system equals 7 days. The change in the average dwell times of vessels, freight wagons and containers according to the varied intensity of freight wagons and vessels before/after optimization of the main dry port parameters is presented in Fig. 9. The change in performance indicators of the seaport – dry port system before/after optimization of the main dry port parameters is shown in Fig. 10.

The presented figures illustrate that optimized values of the main dry port parameters which are applied in ABDES model reduce the average dwell times of container vessels at the anchorage from 7.43 to 2.42 days, Fig. 9a, the average dwell times of freight wagons on private railway tracks in the system from 16.05 to 6.05 wagons-hours, Fig. 9b, and containers in the system from 1.8 to 0.95 days, Fig. 9c.

---

**Table 2.** The technical parameters of the NBCT terminal.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of the berths</td>
<td>units</td>
<td>4</td>
</tr>
<tr>
<td>The total length of the berths</td>
<td>m</td>
<td>1700</td>
</tr>
<tr>
<td>Number of the Ship-to-Shore cranes</td>
<td>units</td>
<td>11</td>
</tr>
<tr>
<td>The storage capacity of the container yard</td>
<td>TEU</td>
<td>42000</td>
</tr>
<tr>
<td>Number of the Rubber Tyred Gantry cranes</td>
<td>units</td>
<td>41</td>
</tr>
<tr>
<td>Number of the reachstackers, terminal tractors, forklifts</td>
<td>units</td>
<td>10 + 36 + 3</td>
</tr>
<tr>
<td>The total length of the railway tracks</td>
<td>km</td>
<td>6</td>
</tr>
</tbody>
</table>

---

Fig. 7. An example of the simulation model block which calculates the key performance indicators of the seaport – dry port system.
Furthermore, the implementation of the dry port with its optimized values increases the container volume of the NBCT terminal by 27%, Fig. 10a. It also reduces the operating costs by 40%, Fig. 10b, and the cost price of container handling by 30% respectively, Fig. 10c. Consequently, with regard to the provided optimization, we obtained the optimal location of the dry port situated 26 km away from the NBCT terminal with its capacity of 750 TEU’s and throughput of transport communications of 23 pairs of trains/day, while the general costs of the construction were reduced by 75%.

5. Discussion

In discussion section, we aim at presenting the following parts of the research: discussion of the findings, theoretical contributions of the present study, practical implications, limitations, and future research perspective.

5.1. Discussion of the findings

As for the first research question about the methodology to develop the seaport – dry port system, this study extends the works on the interaction between marine and intermodal terminals published by (Crainic, Dell’Olmo, Ricciardi, & Sgalambro, 2015; Feng, Zhang, Li, & Wang, 2013; Jeevan & Roso, 2019; Lättilä, Henttu, & Hilmola, 2013). However, in these studies, the various parameters have been applied to set-up the interaction between the seaport and the dry port. It means that scholars have not considered the systematic approach to select and justify the key parameters of the system. Such a non-systematic approach may increase both construction costs of the intermodal terminal and operational costs of the seaport – dry port system as a whole (Muravev, Rakhmangulov et al., 2019). At the same time, in most studies, the environmental parameter has been investigated separately. Authors concentrated on studying the mutual influence between pairs of parameters, i.e. environmental parameter & intensity of traffic flows or environmental parameter & distance between a seaport and a dry port. Meanwhile, in reality, the environmental parameters should be considered systematically (Osintsev & Kazarnshchikova, 2017). In addition, these works do not provide a clear theoretical and practical understanding of how to adjust the interaction between the terminals, and theoretical findings have been proved by empirical evidence.

Turning now to the second research question about the developed ABSDS model of the main dry port parameters, two interesting findings could be emphasized. Firstly, as the developed ABSDS model seeks to achieve the stable state of the parametric system, a similar approach has been applied in other studies (Ostrovsky, 2008; Popov, Krylatov, Zakharov, & Ivanov, 2017). However, these papers only contain the analytical approaches, which are being complexed in the representation of stable dynamic systems. Our study provides a clear theoretical and practical understanding of how to adjust the interaction between the terminals, and theoretical findings have been proved by empirical evidence.

Furthermore, the implementation of the dry port with its optimized values increases the container volume of the NBCT terminal by 27%, Fig. 10a. It also reduces the operating costs by 40%, Fig. 10b, and the cost price of container handling by 30% respectively, Fig. 10c.

Table 3
An example of calibrated coefficients of linear functional dependences.

<table>
<thead>
<tr>
<th>λ</th>
<th>Ttc</th>
<th>V</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.2</td>
<td>0.065</td>
<td>1.25</td>
<td>0.74</td>
</tr>
<tr>
<td>0.27</td>
<td>44</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>0.25</td>
<td>0.01</td>
<td>0.58</td>
<td></td>
</tr>
<tr>
<td>0.25</td>
<td>0.02</td>
<td>1.36</td>
<td></td>
</tr>
</tbody>
</table>

Table 4
The optimal averaged values of the main parameters of the Yiwu dry port.

<table>
<thead>
<tr>
<th>λ</th>
<th>Ttc</th>
<th>V</th>
<th>n</th>
<th>Kt</th>
<th>L</th>
<th>Em</th>
<th>Ef</th>
<th>Gc</th>
<th>Oc</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>23</td>
<td>750</td>
<td>1650</td>
<td>1.2</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>114.65</td>
<td>0.589</td>
</tr>
</tbody>
</table>

(λ) intensity of traffic flows (TEU/day); (Kt) coefficient of variation of traffic flows; (L) distance between the seaport and the dry port (km); (Ttc) throughput of transport communications (pairs of trains/day); (Em) the location of the dry port, characterized by the volume of grading operations at the potential area of dry port location (score); (V) storage capacity of the dry port (TEU); (n) throughput capacity of the dry port (TEU/day); (Ef) environmental factor considered in the dry port allocation (score); (Gc) general costs of the dry port construction (mln USD); (Oc) operational costs of the seaport – dry port system (thous USD).

dynamics approaches, similar models have been designed in the following studies (Djanatliev, German, Kolominsky-Rabas, & Hofmann, 2012; Shafiei, Stefansson, Asgeirsson, Davidsdottir, & Raberto, 2013). On the one hand, the simulation models have been designed in the AnyLogic simulation platform, which is very useful for combining different simulation approaches. On the other hand, the simulation models have been developed for specific cases, i.e. they are not universal. It means that if users aim to study the additional parameters, they should restructure the flowchart, which is time-consuming. Moreover, the application of these models may be difficult in other fields of science.

As far as the third research question about the developed ABDES model of the seaport - dry port system is concerned, the following research findings could be pointed out. From the angle of the hybrid simulation modeling by the AnyLogic software, only one study on terminal operations has been carried out (Abourrajaa et al., 2017). In this study, a similar approach has been proposed, which lies in the application of different agents such as operational planning agents, tactical planner agents, and transport service provider agents. Still, this study is only focused on minimizing waiting situations and unproductive movements in order to improve the productivity of gantry cranes and accelerating container processing at the rail yard of the multimodal terminal. In reality, it is only the sub-task of terminal planning. Besides the crane scheduling, other tasks should be considered in the ABDES model such as searching the optimal location of the terminal, the optimal ratio of handling equipment performing terminal operations, and the evaluation of the total costs of terminal construction and its operation.

In addition, to the best of our knowledge, ours is the first study in the field of logistics and transportation, specifically in terminal planning, which contains two hybrid simulation models based on agent-based, system dynamics, and discrete-event approaches.

5.2. Theoretical contributions

Theoretical contributions are emphasized from three perspectives. Firstly, in previous studies, many scholars applied a wide variety of parameters to evaluate the operational performance of the intermodal terminals. The authors used different terminology to describe the parameters.

Fig. 9. The change in the average dwell times before and after optimization of the main dry port parameters: (a) container vessels at anchorage, (b) freight wagons on private railway tracks of the system, (c) containers in the system.
However, some parameters have identical semantics. Most of the studies related to the main parameters of intermodal terminals have inadequate systematization. In other words, scholars study a separate parameter or investigate the bilateral impact of several external factors on a limited number of intermodal terminals parameters. The stationary view of the limited number of parameters does not allow to reflect complex interactions in dynamics, though, and makes it impossible to find the optimal combination of the parameters values. Collectively, all these drawbacks could increase the total logistic costs. Undoubtedly, these costs have a powerful impact on the operational efficiency of the intermodal terminals.

Consequently, to evaluate the operational efficiency of a dry port, we propose the system of the main ten parameters, the number of which is enough for this purpose. Secondly, this research also emphasizes the lack of studies on direct and inverse relations between the parameters which were applied in the ABSDS model. It means that we investigate the interaction of the parameters dynamically by applying the established functional dependencies between the main parameters of the dry port. Finally, most of the studies investigating the impact of different external factors on the parameters of the logistic facilities are based on the application of the system dynamics approach. It means that scholars have applied a single approach that is not able to scale the simulation model. The capability to scale the simulation model is important if it is necessary to increase the accuracy of the results and provide the micro-simulation. The proposed hybrid agent-based system dynamics model of the main dry port parameters overcomes this challenge.

5.3. Practical implications

Several practical implications can be highlighted in this work from the perspectives of the logistic infrastructure, society and environment.

Firstly, the crucial terminal management problem is to optimize the balance between ship owners and terminal managers. On the one hand, ship owners are aiming to minimize the dwell time of container vessels. On the other hand, terminal managers are willing to maximize the incomes by increasing the storage and handling the capacities of the terminals. Consequently, simulation modeling is better than analytical modeling in representing the random and complex environment of the port facilities with minimal time and labor costs. The planning phases of the intermodal terminal may be supported by means of a developed set of hybrid simulation models. To make the express evaluation of the preliminary intermodal terminal implementation in the pre-planning phase, we suggest applying the developed ABSDS model. We simplify the way of calculating the established

Fig. 10. The dynamics of the following performance indicators of the seaport – dry port system before and after optimization of the main dry port parameters: (a) container volume, (b) operational costs, (c) cost price of container handling.
linear functional dependencies for different stakeholders. It means that port managers, terminal operators or representatives of local governments do not need to calculate the linear functions by applying any sophisticated methods. To clarify the obtained averaged values of the main dry port parameters in the planning operations phase, we propose the application of the developed ABDES model of the seaport – dry port system. It is important for the stakeholders who are making key decisions on the investments into the implementation of the intermodal terminal. Such kind of microsimulation would allow us to identify the bottlenecks in the system operation (Gopalakrishna-Remani, Brown, Shanker, & Hu, 2018). In other words, for each of these phases, distinct simulation tools have been designed. Consequently, even without availing themselves a software engineer’s specialized expertise, users can try several scenarios with input parameters which they have chosen themselves.

Secondly, the emerging seaport disruptions caused by bad weather conditions, frequent changes in the schedules of vessels, and breakdowns of equipment increase the irregularity of container traffic. This irregularity leads to the increased dwell time of vehicles, specifically, freight wagons on railway tracks at both seaport and dry port, container vessels at anchorage and containers in the system. The developed ABDES model of the seaport – dry port system allows different stakeholders such as rail and terminal operators to simulate the uncertain arrivals of vehicles. Such kind of simulation harmonizes and coordinates the operation between the seaport and dry port by the on-time supply of freight wagons from port railway station to both destinations. In other words, the ABDES model could provide the real-time planning of the port operations.

From the perspective of society, since the developed ABSDS model seeks to minimize the distance between the seaport and dry port, the wages of the dry port employees can be potentially increased. One reason is that most of the industry is generally concentrated in/or close to the residential zones. It means that the wages level is highly competitive there because of the wide range of job offers. Another reason is that the minimized distance between the seaport and dry port implies the increase in container volume of the marine terminal and incomes of the system respectively. Consequently, the increased incomes of the system could make the wages of the dry port employees more competitive.

From the environmental perspective, the external environmental factors become extremely important, since there has been an increase in the greening of port facilities (Osintsev & Kazarmushchikova, 2017). It means that the following main parameters of the intermodal terminal have the impact on the volume of the air emissions: the distance between the residential zones and a dry port, intensity of traffic flows and the storage capacity of container yards as well (Muravev & Rahmangulov, 2016). In order to balance the environmental interests with others, we have developed the ABSDS model. The application of the developed model allows different stakeholders to justify technological and reconstruction activities minimizing the environmental impact of the area on the potential dry port location.

In addition, the proposed sustainable approach implemented in the developed multi-agent system dynamics simulation model can be used to solve different kinds of problems. On the one hand, the agents of the developed ABSDS model could represent parameters of different fields of science by establishing the functional dependencies between themselves. On the other hand, the developed algorithm of calibrating the coefficients of functional dependencies allows us to achieve the sustainable operation of the system in the long run. It is crucial for the planning and prediction of different scenarios. Besides, simulation modeling users could improve their research competence by adding more parameters to the ABDS model, which is not time-consuming. The users only need to identify the functional dependencies between the parameters and use an Excel-file. At the same time, they could advance their simulation modeling skills by reconfiguring the blocks of process charts of the ABDES model.

5.4. Limitations and future research perspectives

Some limitations and future research perspectives may be pointed out from theoretical and practical points of view.

From theoretical point of view, the initial values of coefficients in linear functional dependencies could be estimated by fuzzy numbers. Specifically, these fuzzy numbers could minimize the number of ABDS model iterations to reach the sustainable state of the parametric system and increase the accuracy of the results. Furthermore, the initial values of coefficients could be obtained by multi-criteria decision-making (MCDM) techniques (Pamučar, Deveci, Canitez, & Bozanic, 2019; Pamučar, Sremac, Stević, Ćirović, & Tonić, 2019; Stević, Pamučar, Puška, & Chatterjee, 2020; Yazdani, Tavana, Pamučar, & Chatterjee, 2020). In this case, the ABSDS might be improved by its combination with MCDM models.

From the practical aspect, the developed ABDS model of the main dry port parameters could be improved on the part of the programming basics. Since we applied the events from the Agent Library of the AnyLogic software, which is the simplest way to schedule the calibration of the coefficients in linear functional dependencies between the main dry port parameters, the application of fast processing computers is required. In order to overcome this challenge, the developed ABDS model should be improved by minimizing the number of messages transferred between agents-parameters of the simulation model. In other words, the application of the events decelerates the operation of the model. Secondly, the developed agent-based discrete-event model of the seaport – dry port system could be potentially improved through the development of an automated storage yard management system and automated container tracking system by applying artificial intelligence (Duan, Edwards, & Dwivedi, 2019; Dwivedi et al., 2019; Eldrandaly, Abdel-Basset, & Abdel-Fatah, 2019). The proposed improvements could minimize the number of containers movements in the seaport – dry port system and increase their productivity. Finally, the run of the developed simulation models has been carried out separately. It increases the time of collecting and processing the outputs. To overcome this challenge, both models should be integrated at the same time. In fact, the Anylogic software provides the combination of agent-based simulation models with discrete event or system dynamics elements for complete, no compromise modeling.

6. Conclusion

A novel approach is developed to achieve the balance between mutually impacting parameters of a complex dynamic system. This approach is based on the hypothesis about the mutual impact between parameters, which are presented as simple linear functions with further dynamic modeling of parameters values. The novelty of the proposed approach lies not only in the change of the values of the proposed parameters under the impact of the environmental factors but also in the change of the power of the mutual impact between the parameters. In other words, this approach is implemented by adjusting the coefficients in the linear functions depending on changes in the values of the impacting parameters. Consequently, all this completely distinguishes the proposed approach from the well-known models of the adaptation processes in complex systems.

To computationally implement the proposed approach, we developed the hybrid ABDS model whose parameters are represented as the agents. The agents transfer messages between each other, which contain data on their changed values. The internal environment of the agent is presented as the system dynamics model. This model simulates the change of stock (value of the parameter) depending on changes in the reserves of the stocks of all interrelated agents.

In order to provide the sustainability of the ABDS model, we proposed the optimizing add-on with the specified criteria, which allows users to achieve the values of the balanced parameters of the complex system. It was also shown that the developed ABDS model could be applied to the stage of strategic planning of the complex socio-economic systems to achieve the balance between different stakeholders. We proved that the proposed ten main parameters of the dry port are enough to achieve the sustainable state of the investigated complex system, which is the intermodal terminal. It was also suggested that on the stages of real-time and operational management, the most rational way to refine the values of the proposed parameters is the application of the discrete-event simulation model. This model refines the values of
the main dry port parameters depending on the changes in the operational conditions of the seaport – dry port system.

To validate the developed hybrid simulation models and prove their adequacy, we provided the case study on the Yiwu dry port. The obtained data showed that as a result of the increased irregular traffic flows, the models were seeking to minimize the general costs by reducing the distance between the Ningbo-Zhoushan port and the Yiwu dry port. In fact, the Yiwu dry port is located 185 km away from the Ningbo-Zhoushan, while our results obtained by the hybrid simulation models showed its reduction by 26 km. Consequently, the calculated optimal values would affect the total costs of the dry port construction and seaport – dry port system as a whole.

Therefore, through the findings and insights from operational management, this research improves the understanding of the current challenges associated with studying complex systems by acknowledging the critical role of computer-aided learning capability of scholars and practitioners in the field of logistics and transportation.

Credit author statement

D.M., A.R. wrote the manuscript together. D.M. prepared literature review. D.M, A.R. and H.H contributed to the conception of the research and study design. D.M., A.R., P.M. developed the set of the hybrid agent-based models. D.M. collected the data for the case study. H.H. provided critical suggestions and inputs for the case study and helped with writing the manuscript.

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Declaration of interest

None.

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Appendix A

Table A1

<table>
<thead>
<tr>
<th>Name of the block</th>
<th>Description of the block</th>
</tr>
</thead>
<tbody>
<tr>
<td>source</td>
<td>It simulates the agents and serves as the starting point of the agents’ flow. This block generates the following type of agents: vessels, containers, railcars and container lorries.</td>
</tr>
<tr>
<td>queue</td>
<td>It simulates the queue of the agents waiting for the reception of the blocks following this block in the process flowchart. This block generates the following types of queues: downtime of vehicle, container, etc.</td>
</tr>
<tr>
<td>service</td>
<td>It simulates the size of the specified quantity of resources, delaying them, then this block releases the sized resources. This block simulates the following types of delays: loading &amp; unloading operations as well as container handling at the container yards.</td>
</tr>
<tr>
<td>resourcePool</td>
<td>It simulates the set of resources that could be seized by agents. This block simulates the resources of the following types: container lorries, forklifts, cranes, berths, gates, etc.</td>
</tr>
<tr>
<td>moveTo</td>
<td>It moves the agent to a new point. If the agent contains some resources, they are moving together with the agent. This block simulates the movement of vehicles and handling equipment.</td>
</tr>
<tr>
<td>semaphore</td>
<td>It destinies incoming agents to one of the five output ports according to the fulfillment of specified (deterministic or probabilistic) conditions. This block simulates the option of unloading a container vessel by a direct/warehouse variant.</td>
</tr>
<tr>
<td>hold</td>
<td>It locks/unlocks the flow of agents in a particular area of the flowchart. This block simulates the berthing of container ships on the quays of the seaport.</td>
</tr>
<tr>
<td>batch</td>
<td>It converts the specified number of agents entering this block into one agent-batch. This block simulates the combination of container traffic with vehicle flows.</td>
</tr>
<tr>
<td>exit</td>
<td>It retrieves the agents entering this block from the process specified by the flowchart. This block simulates relationships between different types of agents.</td>
</tr>
<tr>
<td>enter</td>
<td>It inserts existing agents at a specific location within the process specified by the flowchart. This block simulates relationships between different types of agents.</td>
</tr>
<tr>
<td>timeMeasureStart</td>
<td>These blocks allow us to measure the time spent by agents between two points in the process flowchart. These blocks calculate the downtime of containers and rolling stock in the system. The data obtained from the presented block is used in calculating the operating costs of the system.</td>
</tr>
<tr>
<td>timeMeasureEnd</td>
<td></td>
</tr>
</tbody>
</table>

D. Muravev, et al.
International Journal of Information Management xxx (xxxx) xxxx


