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Agent-based simulation model of multimodal iron ore concentrate transportation

Abstract. Most global supply chains are implemented through the use of different types of transport. This especially applies to general cargo: iron ore, oil, grain. As the number of participants in the transport process grows, the risks of delays, disruptions which can impact interoperability, and delays in deliveries increase. Therefore, the improvement of multimodal cargo transportation remains an urgent scientific and applied problem. The purpose of the study is to cover the technical and operational parameters of the multimodal supply chain of cargo delivery (on the example of iron ore concentrate). The purpose was achieved by the development of an agent-based simulation model. The AnyLogic Research Edition environment with Java SE was used to implement the simulation model, as it enables the integration of discrete-event and agent-based methodologies in the simulation concurrently. The experimental findings using the developed simulation model revealed the following: 1) around 40% of the delivery time is spent on waiting: 8% for the transport unit to load and 33% for the collection of freight until it reaches the loading rate into the transport unit. 2) the sensitivity

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experiment conducted on the model identified that among all the variable technological parameters in the base model, the difference in the loading rate between the railway train and the sea vessel has the most impact on the average delivery time of freight. 3) there is a strong linear relationship between the vessel capacity (with a constant rate of mass shipment into the railway train) and the average time required for collecting and loading the freight onto the vessel in the event of accidental arrival of freight by rail at the transshipment terminal. The results of the study can be used to improve the logistics chains for the delivery of iron ore concentrate from Ukraine to other countries

Keywords: technological system; optimisation of terminals; Java-code; rail-sea supply chain, system analysis

INTRODUCTION

Globalisation considerably expands the economic and financial capabilities of producers and consumers and leads to an increase in the number of participants in the transportation process. These factors have a detrimental effect on the efficiency of transport production: firstly, unproductive delays occur at transshipment points due to the necessity of collecting shipments for loading onto transport units; secondly, conflicts arise within the transport system due to the technological differences between various transportation modes involved in the multimodal supply chain.

Maritime transport remains the backbone of globalised trade and the manufacturing supply chain. According to the Review of Maritime Transport (UNCTAD, 2022), four-fifths volume of the world merchandise trade is carried by sea. Total volumes grow continually and reached 11 billion tonnes in 2022. Dry bulk commodities contributed considerably to this growth. In 2022, ships spent a median time of 24.2 hours in port. Dry bulk carriers spent 2.11 days in port. Inland distribution, such as railway link, is a vital factor in the performance of global maritime transportation. Given this, the search for optimal parameters in multimodal transportation to minimise delivery time is an urgent scientific and applied task of today. N.Y. Shramenko & O.V. Shramenko (2018) proposed a model for the delivery of bulk cargo by rail transport considering the principles of logistics and system analysis. The optimised technological parameters related to the operation of the whole production and transport chain were justified: the size of the freight shipment, the technical equipment of the freight fronts, and the delivery interval. However, the current model lacks the capability to simulate different scenarios for organising transmitting trains in a transportation junction, specifically for collection up to the required standard, following a strict schedule, and employing a combined approach.

X. Fang *et al.* (2020) proposed to solve multimodal transportations planning problem of inter-organisational coordination by developing an evaluation model of the synergy degree index of container sea–rail transportation actors based on synergy theory. The model enables to produce recommendations to logistics service providers on how to improve their activities to contribute to multimodal transport synergy. The model does not directly address the stochastic nature of multimodal transportation nor give a numerical assessment of its parameters. The competitive advantage of distant hinterland ports is general costs and quality of service. A pricing model, utilising game theory, was proposed by C. Qu *et al*. (2020) to determine the initial equilibrium state of competition among seaports. The proposed model has some limitations because of various business contexts and regulations applied in different countries.

B. Yan *et al.* (2020) addressed the transshipment operation problem through a rolling horizon-based modelling approach that considered the direct transshipment number, storage time, and dwell time of inbound containers. The proposed solution contributes to the minimisation of delivery time in the supply chain but leads to an increase in port service time of trains and supply chain costs. T. Lelke *et al.* (2023) proposed to build the agent-based model using open-source transport statistics. The approach can be applied to different areas and regions of transport services. The study is focused on modelling individual mobility and traffic in the city. combined the agent-based and discrete-event approaches in a simulation model to investigate a two-stage optimisation of intermodal terminal parameters, specifically focusing on the operation of handling equipment and rolling stock (Muravev *et al.*, 2021). The optimisation process aims to minimise container handling costs, which serves as the objective function in this study.

To conclude, modern studies are devoted to solving specific issues of multimodal transport such as operations management, planning, and site location. Besides, they cannot adequately reflect the delivery process in the "rail – sea – rail" system, i.e., from the point of departure to the point of destination, considering the minimum transportation time. The purpose of the study is to analyse the technical and operational parameters of a multimodal supply chain involving a mixed rail-waterborne link for bulk cargo delivery to identify optimal solutions based on the criterion of minimising the delivery time. To address this scientific and practical problem, the proposed approach involves the following steps: developing an agent-based simulation model that represents the transport-technological line of the multimodal railway-waterborne link within the supply chain; conducting experiments using the simulation model to determine the technical and operational parameters that have the most impact on the average delivery time of freight.

MATERIALS AND METHODS

The study considered the rail-sea-rail freight process line, which is a technological system with three interconnected technological elements: the first railway line, the sea line, and the second railway line.

The entire process of freight transportation can be divided into two subsets: the sub-process of freight collection until the required shipment is attained and the sub-process of transporting the corresponding shipment (Fig. 1).

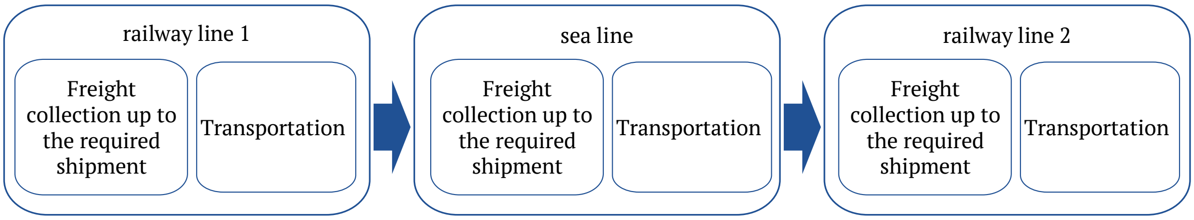

Figure 1. Structural and logical scheme of the simulation model
Source: developed by the authors

The functioning of the third type of agent (Fig. 1) represents the set of sub-processes for both collecting (including the formation of the information order of readiness for shipment dispatch by Agent 2, Table 1) and transportation (involving the operation of the rolling stock by Agent 4, Table 1).

Table 1. Set of simulation model agents

No.	Agent name	Agent function	Simulation - correspondence to the real process
1	The flow of shipment orders	Interaction with other agents as a unit of commodity mass (freight). Fixation of the moment of tracking of a freight shipment of each control point of the simulation	Simulation of advancement of freight through a supply chain, incorporating elements of collecting the freight up to the required level for transportation by a specific mode of transport
2	Information order for a shipment dispatching	Formation of the order for service by the agent of freight transportation	Simulation of the formation of a ready-to-ship consignment by a transport unit – a train or a ship
3	The transport system of a certain type of transport mode (rail or sea) – supply chain	Organization of the transportation process at a certain stage of the supply chain	Simulation of transport production, including freight collection, freight production operations, and freight transportation.
4	Transport unit	Interaction with an information order and a specific transport system	Simulation of transporting a shipment at a certain stage of the supply chain. These sets of agents simulate the direct freight delivery by trains and ships

Source: developed by the authors

The total delivery time of a freight unit is determined by the combined duration of its stay at the collecting point and the transit time during direct transportation:

$$t_{del}=t_{collect.rail1}+t_{tr.rail.1}+t_{collect.sea}+t_{tr.sea}+t_{collect.rail2}+t_{tr.rail2}, \quad (1)$$

Where $t_{collect.rail1}$, $t_{collect.sea}$, $t_{collect.rail2}$ – delay time at the freight collecting point to the required shipment and waiting time for the train, respectively, on railway line 1, sea line and railway line 2; $t_{tr.rail.1}$, $t_{tr.rail2}$ – shipping time of freight by trains on railway line 1 and railway line 2, respectively; $t_{tr.sea}$ – shipping time of freight by ships on sea line.

One of the crucial aspects of optimising the organisation of a multimodal supply chain, considering the cost of shipment, is the minimisation of the average freight delivery time which, obviously, with constant technical parameters of rolling stock (average speed, capacity and other physical and technical parameters) can be achieved by reducing the time of freight collection up to the required shipment and the waiting time of the freight to be shipped by a train:

$$\overline{t_{del}} \rightarrow min\,,$$

where $\overline{t_{del}}$ – average time of cargo delivery, provided:

$$\sum^{\Sigma} t_{collect} \rightarrow min,$$

where $\sum^{\Sigma} t_{collect}$ – the total time of the freight collection up to the required volume (at the point of departure and reloading).

In turn, the waiting time for train when dispatching completed shipments decreased with the growth of the rolling stock:

$$\overline{t_{del}} \rightarrow min\,,$$

provided:

$$\begin{cases} Z \to max, \\ M \to max \end{cases} \quad (2)$$

where Z – fleet of railway rolling stock, trains; M – fleet of water transport vessels (bulk carriers).

On the other hand, increasing the fleet of trains and bulk carriers, while keeping all other factors constant, leads to an increase in the downtime of the rolling stock as it waits for transport orders. Additionally, the loading of the rolling stock is reduced. However, in this context, these changes can be interpreted as improvements in efficiency. The expression (2) was formulated as follows:

$$\sum^{\Sigma} t_{collect} \to min,$$

provided

$$\begin{cases} \frac{\sum \overline{t_{inv.rail1}}}{24} \to min, \\ \frac{\sum \overline{t_{inv.rail2}}}{24} \to min, \\ \frac{\sum \overline{t_{inv.vessels}}}{24} \to min. \end{cases} \quad (3)$$

where $\sum \overline{t_{inv.rail1}}$, $\sum \overline{t_{inv.rail2}}$, $\sum \overline{t_{inv.vessels}}$ – the average daily time of engagement for a unit of rolling stock in railways and water transport, respectively.

Minimisation of loading was achieved by increasing the operational fleet of rolling stock, which is economically inefficient. Hence, the utilisation limit of rolling stock was constrained to a rational limit of 0.5. Formally, the task of finding a rational way of transport production in a multimodal supply chain was to find a solution to the objective function:

$$\overline{t_{del}} = f(Z, M) \to min$$

Provided:

$$\begin{cases} \frac{\sum \overline{t_{inv.rail1}}}{24} \geq 0{,}5; \\ \frac{\sum \overline{t_{inv.rail2}}}{24} \geq 0{,}5; \\ \frac{\sum \overline{t_{inv.vessels}}}{24} \geq 0{,}5. \end{cases} \quad (4)$$

Other limitations and assumptions of simulation also included:

1. the incoming freight flow to the first collection point is the simplest distribution, which follows a Poisson process;
2. the configuration of the infrastructure of railway and sea (port) transport systems is rational and does not considerably affect the time delay in receiving and dispatching trains and vessels;
3. when selecting a server, service channel or service order, the FIFO principle is used (first in – first out) – the server, channel or order being in the longest waiting state is selected;
4. the flow of transportation is one-way: the rolling stock moves in the loaded state in one direction, in the opposite – it is empty.

In this study, the simulation-based approach was employed to analyse the multimodal supply chain of iron ore concentrate (pellets) between Poltava Mining and Processing Plant in Ukraine and Krupp in Germany during 2018-2020, Table 2.

Table 2. Initial parameters of the multimodal supply chain of iron ore concentrate from Ukraine to the EU (Germany)

No.	Parameter	Value
1	Annual volume of shipment, thousands of tonnes	500
2	Railway station of departure in Ukraine	Zolotonneishyne
3	Port of departure (Ukraine)	Southern
4	Port of destination	Amsterdam (Netherlands)
5	Railway station of destination in Germany	Essen
6	Parameters of the railway transport system of Ukraine	
7	Number of cars in the train	56
8	Net weight	3920
9	Parameters of the sea transport systems	
10	Volume of commercial freight of the vessel, thousand tonnes	172.1
11	Parameters of the railway transport system Amsterdam – Essen	
12	Number of cars in the train	45
13	Net weight tonnes	2700
14	Approximate intensity of freight operations, tonnes per minute: loading of cars unloading of cars loading of the vessel unloading of the vessel	 10 20 50 50
15	Approximate intensity	

Source: developed by the authors

Standard statistical methods provided by the "Statistics" library were employed to collect the necessary statistics. The list of the main agents of the model and their functionality were summarised in Table 1. The simulation model was developed using the AnyLogic Research Edition environment with Java SE because it enabled the integration of discrete-event and agent-based approaches, allowing for their simultaneous use in the simulation.

RESULTS AND DISCUSSION

To simulate dynamic transportation processes and capture the state changes of system elements within each individual agent, process modelling libraries for discrete-event simulation are employed. These libraries enable the modelling of various stages such as train arrival for loading, loading, transportation to the unloading point, unloading, return empty run, and all inter-operational downtime (Fig. 2).

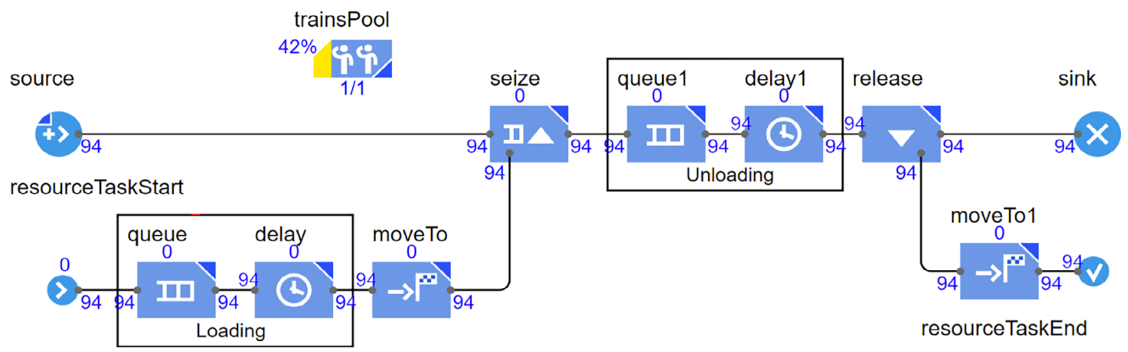

Figure 2. Discrete-event business process of railway line 1 operation (agent railLineOne)
Source: developed by the authors

A new information order is formed as a result of the incoming of the required shipment in the source block.

Further, discretely, the order discretely enters the seize block, where the system captures a free resource (if available) for transportation, specifically, the formed train from the existing fleet, stored within the trainsPool block. In the absence of free resources, the order for transportation is waiting for the released train ready to depart. After capturing the resource (train), it is loaded (queue block – queue formation due to the limited channel of the loading point, and delay block – discrete delay of the train and information order at loading).

Afterwards, the loaded train is simulated to move to the unloading point using the moveTo block. Once again, similar to the loading process, the unloading is discretely simulated within the queue1 and delay1 blocks.

After unloading, the resource (train) is released from the service of the information order (block release) and the block moveTo1 is discreetly returned to the block trainsPool. The information order itself is eliminated in the sink block.

According to this principle, the business processes of all three transport and technological subsystems are simulated: railway line 1, sea line, and railway line 2.

The overall interaction among all agents is facilitated by the Main agent, which simulates the comprehensive multimodal process of the freight supply chain starting from the point of freight collection to the final destination terminal of these products (Fig. 3).

The sourceCargoFlow block generates a shipment orders flow, which corresponds to the incoming of finished products at the warehouse of the manufacturer. Each generated order corresponds to one tonnene of ready-to-ship iron ore concentrate and is generated according to the principle of the Poisson distribution.

The process of collecting orders up to the required volume is simulated in the blocks D_railLineOne, D_seaLine, and D_railLineTwo. These blocks replicate the process of gathering the necessary freight volume to match the loading rate of railway line 1, the sea vessel of sea line 1, and the railway fleet of railway line 2, respectively.

The process of collecting a shipment and forming an information order up to the train's departure is performed by Java-code in each corresponding block type Delay (Fig. 3):

```
«waitForTrainCapOne++;
if (waitForTrainCapOne>= trainCapacity){
  waitForTrainCapOne -= trainCapacity;
    railLineOne.source.inject(1);}»,
```

where waitForTrainCapOne is a variable that indicates the available amount of freight ready to form an information order; train Capacity – rate of loading of a railway rolling stock.

The logic behind this process is that when collecting freight up to the required shipment level, a new information order is generated for transportation by a specific train, represented by the agent railLineOne (Fig. 2).

Once the train arrives at the unloading point and completes the unloading process (in the delay1 block), a Java code is executed, which «skips» the corresponding number of tonnes-orders of freight to the next blocks (D_seaLine and D_railLineTwo) within the main agent:

```
«for (int i = 0; i <main.trainCapacity; i ++)
    main.D_railLineOne.stopDelay
    (main.D_railLineOne.get(i));».
```

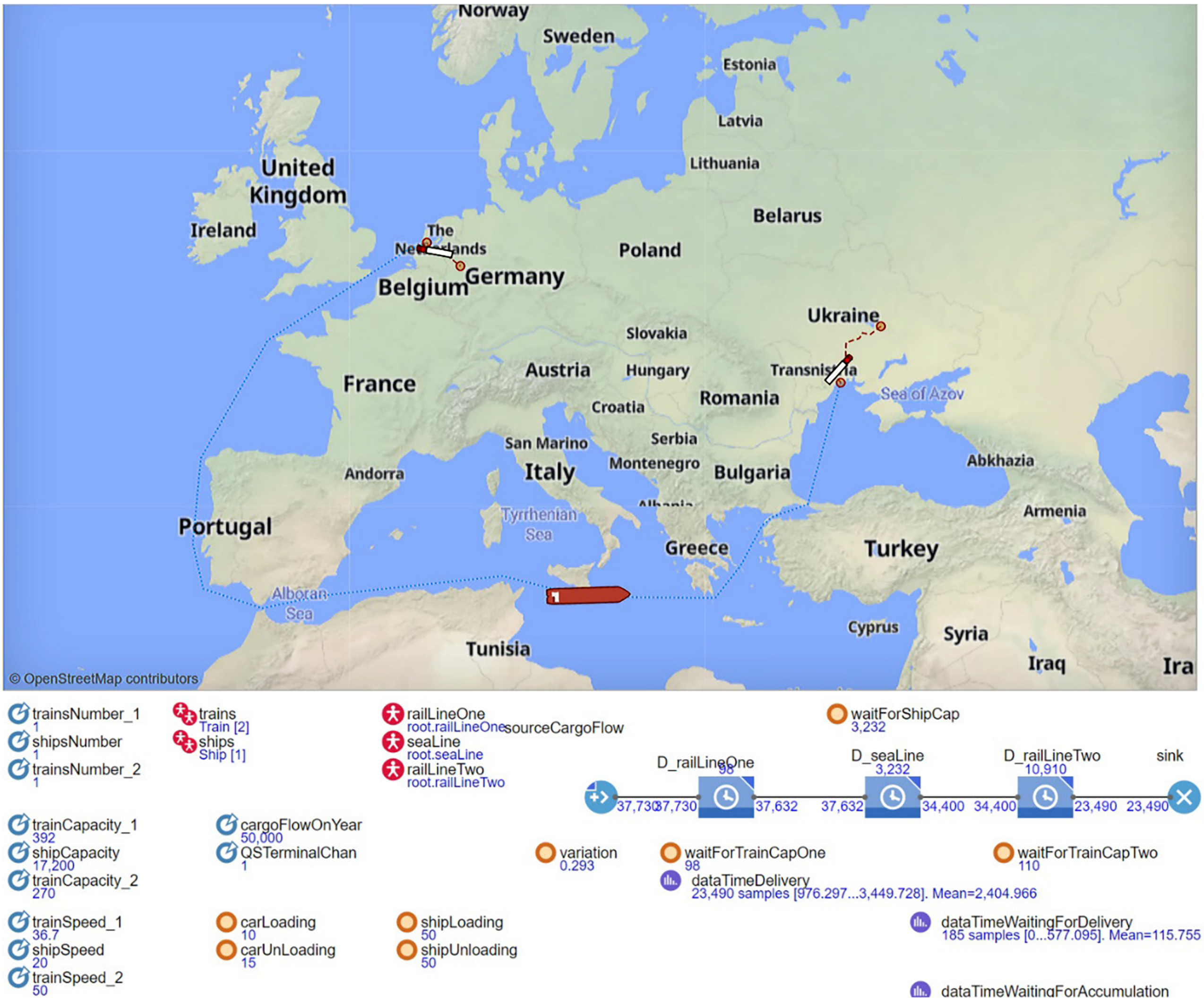

Figure 3. Main Agent window

Implementation of the model.

Based on the simulation of the baseline scenario using the data provided in Table 2, particularly the estimated turnover time of the rolling stock for each line, it can be determined that one unit of rolling stock for each line would be sufficient for handling 500 thousand tonnes of freight per year. The following results were obtained (Fig. 4-6).

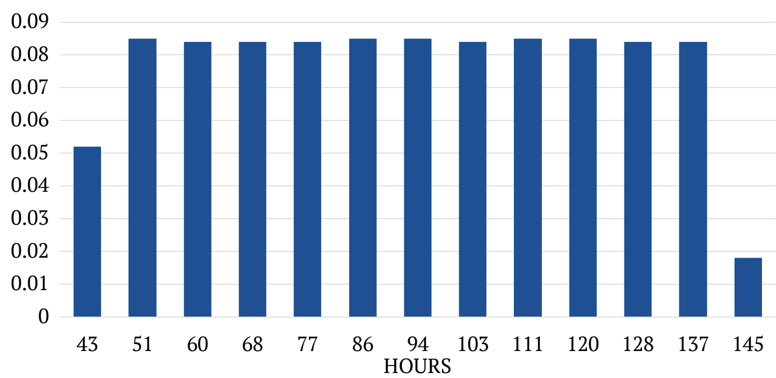

Figure 4. Density of distribution of time of freight delivery

Source: developed by the authors

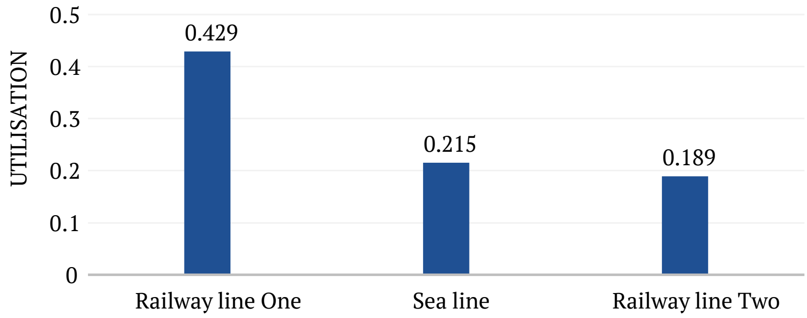

Figure 5. Railway rolling stock and vessels utilization rate

Source: developed by the authors

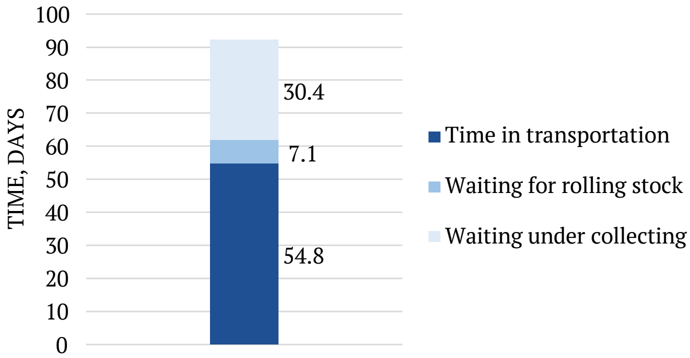

Figure 6. Freight delivery time structure (hours)

Source: developed by the authors

The dependence of the waiting time under collecting on the capacity of the bulk carrier has a clear linear nature, with a coefficient of deviation (determination) R^2=0.9997:

$$T_{aver} = 0{,}0029\, P_{bulk} = 134.77, \qquad (5)$$

where T_{aver} – average waiting time of a tonnene of freight during transportation, hours; P_{bulk} – bulk carrier capacity, tonnes.

The key to the results of this experiment is that even with a significant increase in rolling stock (100 times) from the baseline scenario, the average waiting time at an estimated vessel capacity of 172 000 tonnes will be 638 hours (Fig. 7), which does not differ significantly from the results of baseline scenario with a rational (100 times smaller) fleet of rolling stock.

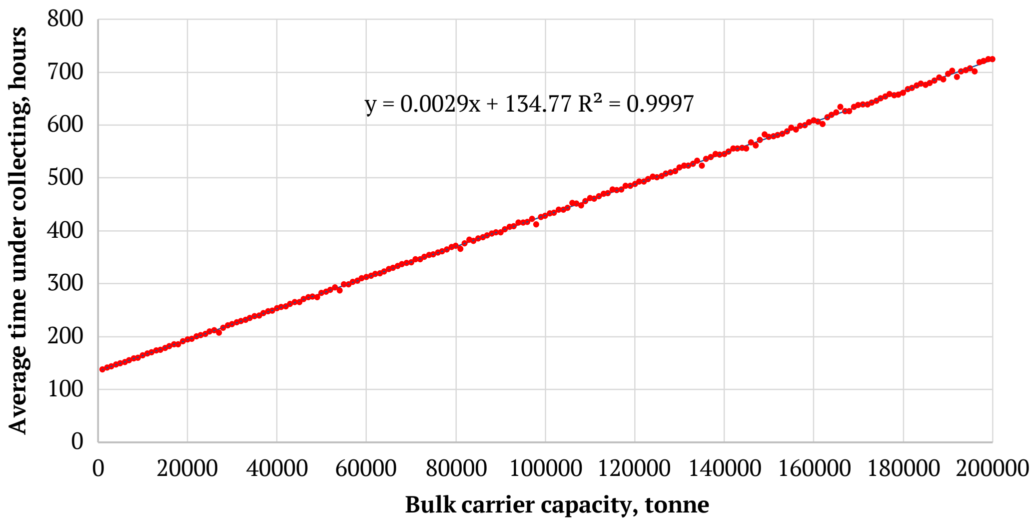

Figure 7. The relation between the average waiting time of the freight under collecting and the rate of commercial capacity of bulk carriers

Source: developed by the authors

Since the duration of direct transportation, which primarily relies on the physical capabilities of transport systems such as the traction characteristics of rolling stock and resistance forces, is a crucial factor, the primary technological criterion for efficient freight delivery organisation is minimising the waiting time of freight at loading and reloading points. Additionally, this total time will encompass both the time taken for freight collection up to the required shipment (based on the commercial capacity of trains and vessels) and the waiting time for an available transport unit (Fig. 6).

The average waiting time for trains depends on the rolling stock, and as can be seen from Figure 6, in the basic simulation, is only 8% of the total delivery time. Delays in delivery often arise from waiting for the rolling stock to be loaded at a slower rate. The efficiency of rolling stock utilisation is greatly impacted by substantial collecting time (Fig. 5), which consistently falls below 50% on all transportation routes. It is considered appropriate to research the interaction of land and sea transportation modes by discrete event simulating (DES) because of the many variables to be analysed together and the necessity of systematic assessment of variables interrelation impact during operational planning, strategic decision-making.

J. Ruiz-Aguilar *et al.* (2016) developed a queuing model network to simulate the container travel time from its departure from the railway terminal to its departure from the seaport using DES. The model was offered as a decision-making tool for intermodal chain planning. H.S. Lopes *et al.* (2017) utilised DES to simulate the overall behaviour of the Brazilian soybean transportation system based on a comprehensive analysis of multiple scenarios.

Agent-based modelling (ABM) has become widely used in transportation, particularly in real-time traffic management and driver behaviour modelling, due to its ability to incorporate detailed information. Variables like travel time reliability, average speeds, and work zone capacity can be effectively analysed using ABM (Abdulsattar *et al.*, 2019; Chargui *et al.*, 2019; C. Wang *et al.*, 2019). Grobarcikova and Sosedova (2016) utilised ABM to investigate the effects of barge location, water level, and transit time on intermodal transportation costs in Danube's container transport.

V. Reis (2019) simulated the decision-making process of individual agents in the administrative and physical layers through a normative stepwise approach using fuzzy set theory and accumulated market knowledge. The model allows assessing the influence of agents' market-related measures and behaviour on their competitiveness and the respective transport chain. M. Le Pira (2018) used ABM to simulate opinion dynamics in stakeholder networks. Individual stakeholders were represented with characteristics like opinion and influence, and they interacted based on simple behavioural rules to observe the convergence of opinions. The author did not mention uncertainty of transportation process. K. Chargui *et al.* (2019) proposed a reactive multi-agent system for simultaneous (re)scheduling of vessel, quay crane, operator, and trucks each hour.

A multi-agent simulation model was developed using the AnyLogic simulation platform to enhance container processing efficiency at the rail yard of the multimodal terminal in Le Havre seaport. The model primarily focused on minimising waiting time and unproductive movements of gantry cranes (Abourraja *et al.*, 2017). Nevertheless, the authors have not represented the vehicles and handling equipment as the agents, which could simplify the understanding of the interaction between agents. R. Elbert *et al.* (2017) developed combined agent-based and discrete event model to investigate the impact of different order release times on the process efficiency of the individual actors (intermodal agency and rail transport company) and the export-oriented container transport chain in Germany in total. However, the authors have not differentiated orders according to their contents. The utility of the AnyLogic simulation platform in addressing facility planning challenges has been demonstrated (Borshchev, 2014), which is particularly effective in multimodal and intermodal transportation, including modelling the receiving and processing of trains (Matsiuk *et al.*, 2019), analysing operational processes in railway stations and marshalling yards (Baugher, 2017; Matsiuk, 2017), and strategically planning intermodal terminals and dry ports (Abourraja *et al.*, 2017).

V. Matsiuk *et al.* (2019) utilised the AnyLogic platform to develop discrete-event models that focused on effectively organising transmitting trains according to a "tight schedule" and efficiently collecting trains based on the loading rate. The implemented model was specifically designed to handle container traffic between the dry port Odesa-Lisky and Odesa-port in Ukraine. To conclude, the novelty of this study compared to previous ones lies in the application of ABS to optimise technical parameters in the multimodal supply chain, while also providing detailed analysis of each component.

In contrast to other studies, the given one conducted an experiment to assess the sensitivity of parameter changes to determine the root cause of considerable delays in freight delivery during the collection process for the required shipment. The essence of this experiment is to identify the parameter of transportation, which with all other constant parameters has the greatest impact on the efficiency of transportation. In this case, the efficiency criterion is defined by the total average time it takes for the freight to be collected at the required rate. To minimise the impact of other parameters on the specified efficiency criteria, the rolling stock in the simulation was increased 100 times. Among the experiments, the greatest influence is exerted by the ratio of capacity between trains and vessels. That is, the closer, in absolute terms, the useful capacity of the vessel to the capacity of the train, the more efficient this process is.

CONCLUSIONS

The developed simulation model combines discrete-event and agent-based principles, simulates a supply chain with three transport and technological lines: rail 1, sea, and rail 2, considers various technical and operational parameters such as planned annual freight flows, transport unit loading rates, delivery speeds along the routes, the number of service channels, and productivity during freight reloading at the junction. The model also accounts for the random nature of freight arrivals at the point of departure, as well as the required fleet size of transport units.

Experimentally, the following has been found:

1. In the basic simulation, approximately 40% of the delivery time is spent waiting for the transport unit to load (8%) and freight being collected up to the loading rate into the transport unit (33%).

2. The sensitivity experiment of the model determined that of all the variable technological parameters of the basic model, the difference in the ratio between the rate of loading of the railway train and the sea vessel has the greatest influence on the average time of freight delivery.

3. The relationship between the capacity of the vessel (with a constant rate of mass shipment into the railway train) and the average time of shipment collection to the loading rate into the vessel, in the event of accidental arrival of freight by rail at the transshipment terminal, shows a highly approximate linear dependence. In further studies, it is necessary to explore other ways of delivering goods. For example, using road transport. Especially for the transportation of other types of goods, such as grain or food.

CONFLICT OF INTEREST

None.

ACKNOWLEDGEMENTS

None.

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Розробка агентної імітаційної моделі мультимодальних перевезень залізорудного концентрату

Анотація. Більшість глобальних логістичних ланцюгів реалізуються за допомогою різних видів транспорту. Особливо це стосується генеральних вантажів, таких як залізна руда, нафта, зерно. Зі зростанням кількості учасників у транспортному процесі збільшуються ризики затримок, збоїв у роботі та невиконання термінів доставках. Тому покращення мультимодальних маршрутів постачання вантажів залишається актуальною науково-прикладною проблемою. Метою дослідження було вивчити техніко-експлуатаційних параметрів мультимодального ланцюга постачання вантажів (на прикладі перевезення залізорудного концентрату). Для цього була розроблена агентна імітаційна модель. Імітаційна модель реалізована у середовищі Any Logic University Researcher з використанням компілятора Java SE, оскільки цей інструментарій дозволяє одночасно поєднувати дискретно-подієвий та агентний підходи. В результаті експерименту з імітаційною моделлю було встановлено, що: 1) приблизно 40 % часу доставки припадає на очікування вантажем транспортних одиниць для завантаження (8 %) та перебування вантажу під накопиченням до норми завантаження транспортної одиниці (33 %); 2) експеримент чутливості моделі визначив, що з усіх змінних технологічних параметрів базової моделі найбільший вплив на середній час доставки вантажів має різниця у співвідношенні між нормою завантаження залізничного маршруту та морського судна; 3) залежність між місткістю судна (при рівномірному надходженні вантажу у пункт навантаження) і середнім часом накопичення партії вантажу до норми навантаження у судно, апроксимується лінійною залежністю. Результати дослідження можуть бути використані для вдосконалення технологій транспортування залізорудного концентрату з України в інші країни

Ключові слова: технологічна система; оптимізація роботи терміналів; Java-код; залізнично-морський ланцюг постачання; системний аналіз