Design and Optimization of Maritime Transport Infrastructure Projects Based on Simulation Modeling Methods

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Abstract. The majority of strategic development projects of transport infrastructure require significant investments and intended for long terms of implementation. In this respect, the efficiency of transport systems, as a rule, depends on a large number of factors, many of which are prone to random changes. Consequently, planning and optimizing the elements of transport systems at the project development stage is an important and often very difficult task. In some cases for the effective solution of this problem, taking into account the specifics of all technological processes can be successfully used simulation modeling methods. Paper deals with the practical problems, which have arisen during implementation of the project of a justification of the optimum plan for modernization of infrastructure of the Ro-Ro terminal of port Emden, are considered. The ways of resolving these problems using the methods of simulation modeling specified.

Keywords: maritime transportation, multimodal logistics, simulation modeling, optimization of transport infrastructure, Ro-Ro terminal.

1 Introduction

The efficiency of modern logistics hubs largely depends on the coherence and coordination of a large number of processes running in parallel, as well as the management of available resources. Characteristics of cargo flow, specifics of navigation, weather conditions, specifics of operation of associated modes of transport and a number of other factors have a significant impact on the performance indicators of port terminals. Herewith, the tasks of organizing the work of terminals are often complicated because the intensity and structure of cargo flows in the future may be subject to significant variations. A number of scientific works are devoted to research in this field.

The paper [1] discusses the way logistics service providers use the terminals in their supply chains. It addresses how the development of seaport and inland terminals affects supply chains by increasingly confronting market players with operational considerations such as imposing berthing windows, dwell time charges, truck slots, all

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this to increase throughput, optimize terminal capacity and make the best use of available land. The article [2] examines port and container terminal characteristics such as location, physical infrastructure and service, and assesses how they affect performance.

Influence of a choice of structure of park of the equipment and management of its updating on indicators of efficiency of functioning of the sea terminal has been studied in work [3-8]. In work [3] a simulation model for search and solution of the problem of optimal fleet structure of sea port equipment has been introduced. In work [4] estimations of fluctuations of operational indexes and stability of economic indexes of equipment working under unstable load have been received. Assuming that the flow of incoming cargoes described by a complex Poisson zero-drift model, a system of integral differential equations with corresponding boundary conditions was derived and studied in order to find the limit of joint distribution of the number of docked vessels and the number of cargoes in the warehouse. In work [5, 6] estimates of variations of operational parameters and stability of economic indicators of equipment working under conditions of unstable load obtained. In works [7, 8] questions of development of terms of major repair and replacement of the seaport equipment with account of deterioration are studied.

Modern sea terminals are, as a rule, the centers of conjugation of several modes of transport: sea, railway and automobile. Therefore, the organization of interaction between different modes of transport is of great importance in terms of performance indicators of the terminal. There are a number of works devoted to studying these issues [9–11].

Improving the efficiency of transport systems requires the introduction of new technologies and the use of advanced planning methods. At present, integrated electronic information tools are being actively developed and used to improve the efficiency of transport systems through better coordination of cargo transportation and optimization of the use of valuable resources.

While creating decision support systems aimed at substantiating the choice of the integrated transport infrastructure development strategy, project planning and management of the design, creation and use of specific software are of high significance. There is a number of works aimed at developing and improving project management methods. In the article [12] the method of selection of effective criteria for investment projects evaluation is offered, based on the analysis of methods of portfolio investment formation on the basis of combined methods of DEMATEL and ANP modeling. In work [13] the complex basis of the analysis of the project success as a new knowledge-based approach to project management is presented. In [14] the conceptual model of the system "project map - criteria - constraints" developed, which can serve as a universal basis for the formalization of decision-making processes on the choice of the project, taking into account possible modules of project characteristics.

Despite the significant development of classical mathematical methods of operations research, the range of practical problems, they can be effectively applied, quite limited. Therefore, in many cases, in the study of complex transport systems is the most appropriate application of simulation methods. In work [15] developed a decision support system based on simulation modeling to optimize shipyard operations by taking into account all cargo flows through the shipyard in order to improve the efficiency of container terminal operations. To optimize the system of perishable cargo delivery through the port of Odessa, a discrete event simulation model was implemented in [16]. In [17], a simulation modeling method was used to analyze bulk cargo unloading, as well as the transportation, storage and offloading of materials at RUSAL's alumina refinery Auguinish alumina. Another simulation model was implemented in [18] in order to replicate the work performed in the intermodal container terminal, as well as to calculate the total time of transportation and to identify bottlenecks. There are a number of other publications in which the simulation approach has been successfully applied to study complex systems, including those related to transport and logistics. And despite the large number of publications, as well as the ever-growing interest in this area, a number of practically important issues still remain under-researched.

2 Statement of the problem for the Emden's port Ro-Ro terminal modernization

As part of the business project study, our team investigated the performance of the Emden Ro-Ro port terminal with various options for its upgrading under various traffic flow scenarios. Located in the depths of the River Ems, this terminal is a major Ro-Ro cargo hub with a daily carrying capacity of over 5,000 export and import vehicles. In assessing the performance of the terminal, it was necessary to consider and integrate the schedule of shipping lines, the nature of cargo flows, the characteristics of the terminal and the prevailing natural conditions of river navigation.

Due to the daily high tide, the movement of deep-drafted vessels along the Ems River is limited for a significant part of the day. In order to reach the berths of the port, vessels have to be at a certain point in time, maintain a certain speed limit and eventually meet with tugboats for mooring.

The movement of vessels from the anchorage point to the berths of the terminal takes on average about 3.5 hours. The depth of the river fairway varies from 14.23 m to 10.5 m. The amplitude of water level changes due to tidal movement exceeds 6 m. Vessels unable to pass through the estuary before low tide have to wait at the roads or at the pier in order to reach the next tide. This has a significant impact on the terminal operations and makes it difficult to predict the KPI values of the terminal in the event of increased intensity or irregularity of cargo movements as well as increased draft from inbound vessels.

Taking into account possible changes in cargo structure and vessel traffic, it was necessary to consider several options for modernization of the terminal infrastructure. In our approach, we assessed the performance of the terminal and the stability of each of the modernization options, taking into account all possible changes.

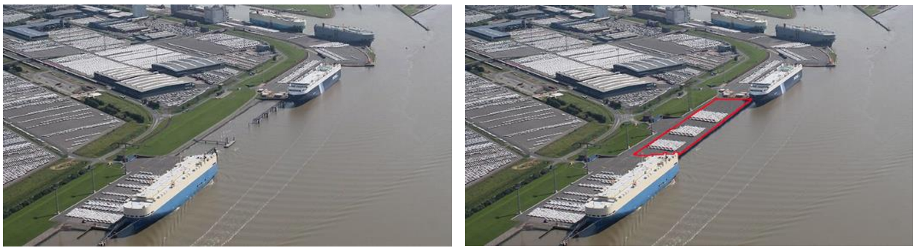

Fig. 1. Emden Ro-Ro terminal before and after the planned construction of an additional deep-water berth [19].

The construction of an additional deep-water jetty (Figure 1), various dredging options, increased stevedoring intensity and variety of combinations of these measures were considered as a possible option for the upgrade of the terminal.

3 Development of a simulation model of terminal operations

Since classical analytical methods of queue theory and optimal control methods do not allow investigating the problem in full, modeling methods were used. The discrete event simulation model developed implemented as a separate application software with a graphical interface, data input, verification and output functions, as well as three-dimensional animation. Animation with the execution of a simulation model of the Ro-Ro terminal in the Emden port while working in 3D presentation mode is available at [20].

Immediately after start-up, the program reads the input parameters of the model from the corresponding structured file. This file contains all information about terminal modernization parameters, cargo flow change scenarios, vessel call schedules, number and capacity of tugboats, operation of stevedoring personnel, general simulation model parameters, etc. One single input data file corresponds to a specific scenario variant of the terminal modernization and cargo flow development. Such file contains more than 500 model parameters.

Given the large number of input parameters, to prevent possible errors in data input, the program checks and thoroughly analyzes the input data for integrity, correctness and consistency before starting the simulation. If inaccurate or inconsistent information found in the input data file, the program helps to correct it.

The proposed simulation model can work both in single-pass mode with 3D-animation [20] and in high-speed multi-pass mode without visualization. When working in 3D presentation mode, the model displays real-time animation of processes taking place in the terminal.

Fig. 2 shows the working windows of the simulation model, working in a single mode, with a 3D presentation that displays one of the options for modification of the terminal. In the upper part of the model window there is a dynamic water level graph. Right below the water level chart there is a dynamic chart, where you can see the commencement and the completion of each stevedoring shift taking into account weekends and holidays. It is also possible to monitor how the terminal redistributes stevedoring gangs between berths during operation, while at the same time observing the intensity of loading and unloading operations at each berth of the terminal. Cylindrical columns of blue and red above the berths in the 3D presentation window show the status of the loading/unloading process. Indicators depicted above the buoys along the fairway show the change in the current water level in different parts of the vessel's route. Simulation of the water level in the river at each point of time was performed with an error of ± 0.01 m.

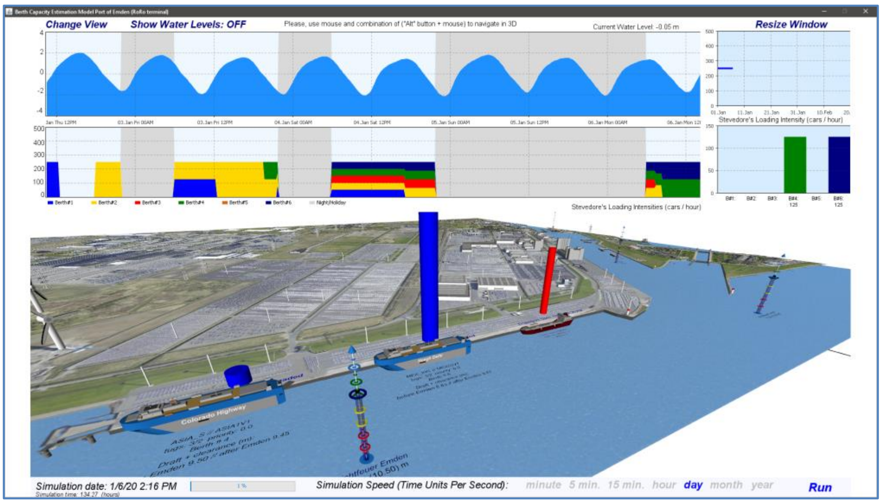

Fig. 2. Simulation model window during the run in the 3D presentation mode.

Creating a simulation model, the algorithms that simulate the work of the traffic control services of the terminal were implemented. The developed algorithms made it possible to regulate movement of vessels along the Ems river most effectively taking into account changes in the water level in each section of the fairway, as well as control the operation of the tugboat fleet.

Much attention was paid to reproduce the schedules of vessel calls with high accuracy – technical characteristics of the ships, loading and unloading rates as well as seasonal changes in cargo traffic and possible effects of random factors were taken into account.

The model allows to display the movement of vessels operating on linear services whose voyages executed in accordance with a fixed schedule on certain destinations as well as the movement of tramp vessels with a random appearance.

There is also a prioritization mechanism used for different groups of vessels and different destinations, priorities can be set for selected shipping services or berths, and the rules of rotation have been taken into account.

Along with the design of business logic, the development of algorithms and visualization tools, the most important aspect of creating this simulation model was the choice of the structure of input data and the organization of data input and output. On one hand, the chosen structure of the input data allowed to reproduce the specified schedules of vessel calls quite accurately so that it was possible to check the adequacy of the model on the actual data of previous years, and also it was possible to investigate the operation of the terminal in the short-term prospects. On the other hand, the proposed structure of the input data made it possible to effectively specify scenarios of cargo traffic that are likely in the distant future and for which there are no exact schedules of vessels, but only a specification of trends.

Much attention was paid to measures that contribute to maintaining the integrity and correctness of the input data. For this, firstly, various visual tools, comments and contextual prompts that appear while editing the input data file were used to help make data entry more convenient and more intuitive. Secondly, a two-level verification of the input information was implemented. The first level of verification was implemented at the stage of editing the input data file. At this level, most typos and apparent inconsistencies are detected and corrected. The second level of input data verification is carried out by the simulation model right before the start of the model run. At the second level, a series of more complex checks and test calculations are carried out, aimed at detecting non-surface logical inconsistencies and contradictions.

After completion of the run, the model generates output file containing both the general statistical indicators of the terminal's operation for a given period of time as well as detailed protocol with a record of all events that occurred at the terminal during the run of the model. Analyzing this file, one can, firstly, check the adequacy of the work of all elements of the model, and secondly, track the occurrence of crisis phenomena and observe the appearance of queues and analyze the circumstances that caused them. It also allows to evaluate how quickly the system is able to overcome crisis situations and the lack of resources at the same time.

Random number generators can be configured in the model so that all the processes occurring on the terminal are reproduced in the same way from start to finish. This allows you to see how well the system is able to cope with the same crisis conditions in various terminal upgrade options. Additionally, random number generators can be configured so that each launch creates a unique sequence of random events. This mode is useful when studying the stability of the terminal performance.

The most important information about the performance and stability of the terminal operations can be obtained by analyzing a series of runs of the simulation model under various options for its modernization. The simulation model algorithms are optimized in the way so that it takes less than one second to run a single scenario within one year of model time. This makes possible to carry out numerous series of tests and crate on their basis the set of statistical conclusions or use various numerical algorithms to find the optimal parameters for the modernization of the concerned terminal. Upon completion, the model saves all the resulting data of a series of runs to a respective output file.

4 Simulation Results and Discussion

On the basis of the analysis of statistical data obtained as a result of numerous repeated runs of the simulation model, it is possible to estimate the average value of key performance indicators in various situations, in the future - resistance to possible fluctuations in freight flows and random deviations in the traffic schedule, thus, the deficiencies of the considered transport system were identified. A number of estimates have been obtained for different freight flow scenarios and various options for modernization of the terminal, such as average ship's downtime on the raid, values of berth employment ratios, etc. Distribution density functions for the values of key performance indicators and confidence intervals for their assets have been defined.

A series of voyages were conducted in order to assess how well the various options for the development of the terminal will function in conditions of increasing cargo flow. The results of the turnovers were used to build appropriate charts of the values of the key performance indicators. The diagram on the Fig. 3 shows the berthing time for only four alternative options for upgrading the terminal infrastructure with a gradual increase in traffic.

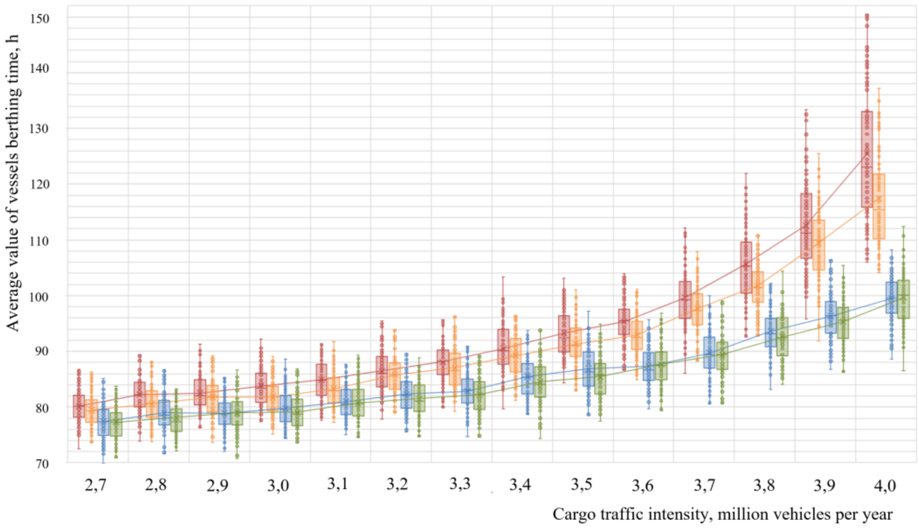

Fig. 3. Changes in the average value of vessels berthing time for the three options of the terminal development according to changes of cargo traffic intensity.

Each of the points depicted in this figure shows the average vessels berthing time for one run of the simulation model, which corresponds to one year of operation of the terminal. Each box shows the values between the upper and lower quartiles of the sample of mean values of the average vessels berthing time obtained at a given cargo flow intensity for a given terminal development option. Fluctuations of values within the box are due to random events and inconsistencies in the working time of stevedores, the schedules of the ships as well as tides etc. The curves on Fig. 3 reflect changes in the average values of vessels berthing time for all runs, depending on the intensity of cargo throughput.

Note: Fig. 3 should be taken only as a schematic indication that presents implemented methodology in this research project. Due to commercial secrecy, publication of actual trade data and detailed simulation conclusions is not possible. Therefore, the data shown in Fig. 3, were intentionally modified. The figure also illustrates the overall trend of changing the mean and the level of stability for the quality of service of the ships identified in the study.

It can be seen from the Fig. 3 that at a low intensity of cargo traffic (from 2.7 to 3.5 million vehicles per year), there is a slight gradual increase in the average vessel berthing time. At the same time, all four curves of the mean values are almost parallel, and the degree of variation of the average vessels berthing time is rather small and almost the same for all four variants of terminal modernization. But with a significant increase in cargo traffic intensity (more than 3.7 million vehicles per year or more), there is a significant nonlinear increase in both the average value and the degree of scatter in the first and second variants of terminal upgrades. At the same time, with the third and fourth variants of the terminal development, both the mean values and the range of values are increasing at a much slower rate.

5 Conclusions

The main purpose of this research project was to justify the strategic plans of the future terminal development. However, it would be impossible to find firm solution without in-depth analysis of the specifics of operational processes at their lower managerial level. Development and implementation of control algorithms of processes occurring at the operational level caused the main difficulties in creating this simulation model. Thus, among such algorithms were the operational control of the vessels movement at the mouth of the Ems river that takes account of the dynamics of the sweep of the tides, algorithms for the operational distribution of the tugboat fleet and stevedoring brigades etc.

When modeling transport systems, the adequacy of the elements such as traffic schedules of vehicles, accurate description of all technological operations associated with service and cargo handling as well as taking into account the possible effects of random factors are of great importance. However, no less important, and in some cases a much more complex aspect, is the simulation of the work of traffic control services. The traffic control service is engaged in the optimization of the vehicle movement, coordination of various processes going in parallel, as well as the operational redistribution of available resources. Modern traffic control services are quite complex man-machine systems. The performance and stability of most transport systems significantly depends on the performance of these services. Therefore, modeling the work of traffic control services is an important and, as a rule, the most time-consuming part of creating simulation models.

Use of simulation models allow to obtain accurate estimations of the key performance indicators and evaluate sustainability of complex transport systems, which in turn allow to justify necessity of additional equipment or resources, to obtain estimates of the system throughput, to justify the tariffs, as well as to simulate the development of possible crisis situations and explore a number other issues. Despite the complexity of the simulation models design, difficulties in collecting and analyzing input and output data, the practicability of using such an approach in many cases is due to its high efficiency and accuracy.

References

1. Rodrigue, J. P., Notteboom, T.: The terminalization of supply chains: reassessing the role of terminals in port/hinterland logistical relationships. Maritime Policy & Management 36(2), 165-183 (2009), https://doi.org/10.1080/03088830902861086.
2. Felício, J. A., Caldeirinha, V., Dionísio, A.: The effect of port and container terminal characteristics on terminal performance. Maritime Economics & Logistics 17(4), 493–514 (2015), https://doi.org/10.1057/mel.2014.33.
3. Pasichnyk, V., Kunanets, N., Veretennikova, N., Rzheuskyi, A., Nazaruk, M.: Simulation of the social communication system in projects of smart cities. In proceedings of the 14th International conference on Computer sciences and Information technologies (CSIT 2019), Lviv, Ukraine, pp. 93–98 (2019).
4. Postan, M., Kushnir, L. A: method of determination of port terminal capacity under irregular cargo delivery and pickup. Eastern-European Journal of Enterprise Technologies 4(3(82)), 30–37 (2016), https://doi.org/10.15587/1729-4061.2016.76285.
5. Lapkina, I., Malaksiano, M.: Estimation of fluctuations in the performance indicators of equipment that operates under conditions of unstable loading. Eastern-European Journal of Enterprise Technologies 1(3(91)), 22–29 (2018), https://doi.org/10.15587/1729-4061.2018.123367.
6. Malaksiano, N. A.: On the stability of economic indicators of complex port equipment usage. Actual Problems of Economics 12(138), 226–233 (2012).
7. Nemchuk, O. O.: Specific Features of the Diagnostics of Technical State of Steels of the Port Reloading Equipment. Materials Science 53(6), 875–878 (2018), https://doi.org/10.1007/s11003-018-0148-5.
8. Nemchuk, O. O.: Influence of the Working Loads on the Corrosion Resistance of Steel of a Marine Harbor Crane. Materials Science 54, 743–747 (2019), https://doi.org/10.1007/s11003-019-00241-y.
9. Hu, Q., Wiegmans, B., Corman, F., Lodewijks, G.: Integration of inter-terminal transport and hinterland rail transport. Flexible Services and Manufacturing Journal 31(3), 807–831 (2019), https://doi.org/10.1007/s10696-019-09345-8.
10. Panchenko, S., Butko, T., Prokhorchenko, A., Parkhomenko, L., Zhurba, O.: Development of rational rail network topology for high-speed and conventional trains based on bacterial foraging optimization. International Journal of Engineering & Technology 7(4.3), 217–221 (2018), http://dx.doi.org/10.14419/ijet.v7i4.3.19790.
11. Lomotko, D. V., Alyoshinsky, E. S., Zambrybor, G. G.: Methodological Aspect of the Logistics Technologies Formation in Reforming Processes on the Railways. Transportation Research Procedia 14, 2762–2766 (2016), https://doi.org/10.1016/j.trpro.2016.05.482.
12. Sachenko, O., Hladiy, G., Bushuyev, S., Dombrowsky, Z.: Criteria for selecting the investment projects on DEMATEL and ANP combination. In: 8th International Conference Proceedings on Intelligent Data Acquisition and Advanced Computing Systems: Technol-

ogy and Applications (IDAACS) pp. 555-558. IEEE, Warsaw, Poland (2015), https://doi.org/10.1109/IDAACS.2015.7341366).
13. Todorović, M. Lj, Petrović, D. Ć, Mihić, M. M., Obradović, V. Lj., Bushuyev, S. D.: Project success analysis framework: A knowledge-based approach in project management. International Journal of Project Management 33(4), 772–783 (2015), https://doi.org/10.1016/j.ijproman.2014.10.009.
14. Rudenko, S., Andrievska, V. Concept of project selection and its formalization in the absence of complete information. Eastern-European Journal of Enterprise Technologies 2(3(80)), 4–10 (2016), https://doi.org/10.15587/1729-4061.2016.65618.
15. Hadjiconstantinou, E., Ma, N. L.: Evaluating straddle carrier deployment policies: a simulation study for the Piraeus container terminal. Maritime Policy & Management 36(4), 353–366 (2009), https://doi.org/10.1080/03088830903056991.
16. Lapkina, I. O., Malaksiano, M. O.: Modelling and optimization of perishable cargo delivery system through Odesa port. Actual Problems of Economics 3(177), 353–365 (2016).
17. Cimpeanu, R., Devine, M. T., O'Brien, C.: A simulation model for the management and expansion of extended port terminal operations. Transportation Research Part E: Logistics and Transportation Review 98, 105–131 (2017), https://doi.org/10.1016/j.tre.2016.12.005.
18. Baldassarra, A., Impastato, S., Ricci, S.: Intermodal terminals simulation for operation management. European Transport, Institute for the Study of Transport within the European Economic Integration 46, 86-99 (2010).
19. Port of Emden, http://www.seaports.de/virthos.php?en//HOME/HAFENSTANDORTE/Emden, last accessed 2019/11/20.
20. Animated presentation of the Emden Ro-Ro terminal simulation model, https://drive.google.com/open?id=11cchJszdOiC_mOF0sOXtgi27FHqlSqsW, last accessed 2019/11/20.