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INFRASTRUCTURE CHANGES OF THE SEA PASSENGER PORT BASED ON A DIGITAL TRANSPORT MODEL

Summary. Marine passenger ports and terminals are key transport facilities that influence the development and positioning of a region, city or country. The port infrastructure should provide the world requirements in service of cruise and ferry ships, and ensure the efficiency and convenience in service of passengers and associated cargo flow. This circumstance determines the necessity of infrastructure modernization, and hardware and software renewal. At the same time, the existing equipment in ports and terminals is gradually becoming outdated, hence the necessity of modernization on the basis of development of a decision-making system. This decision-making system should no longer be based on analytical models, but on new digital transport models of sea passenger ports and terminals. These digital models must take into account both passenger handling processes and external processes for handling cruise and ferry ships. The model should have high computational power and take into account the influence of the external environment. These models should answer development forecasting questions and provide an accurate decision-making system for the validity of infrastructure changes. The Passenger Port of Saint Petersburg "Marine Façade" (St. Petersburg) was chosen as the subject of research. To construct a numerical model, port operation intensity, passenger, cruise and ferry vessel handling processes were investigated; port and terminal development strategies and the mutual influence of the "city-port" systems on each other were studied. As a result of the analysis, a new digital transport model of the sea passenger port was built, which has a high level of detail and accuracy of process implementation, high productivity and efficiency of analysis of various infrastructure changes in the port, allowing the inclusion of dynamic changes from the external environment. The numerical model has been fully implemented for this port, and new conclusions have been derived from it. The use of these new models allows justification of infrastructure upgrades and to study the position of the port in the region in relation to competitors' ports. The developed tool allows solving the problem of research on port processes at any level of planning and enables integration into the information systems already existing in ports and terminals.

1. INTRODUCTION

It is well known that theoretical approaches to port development have been developed over the years, during which various researchers attempted to explain the complex process of port development by proposing various models of a qualitative, descriptive nature. In the models considered by the authors [1-6], it was implied that the sea passenger port represents a certain stage of development of the main cargo port. However, today, the situation is quite different. Sea ports of passengers and terminals are separate large transport systems, developing separately according to their own laws, which have a direct impact on the city, region and the international position of the country. The seaport of passengers is a source of new infrastructure requirements for modernization. At the same time, it is influenced by global processes and industry trends, as well as oriented to the requirements of cruise and ferry tour users. Being separate transport systems, sea passenger ports require the use of their own models and methods to justify the modernization of infrastructure and solve the problem of forecasting development. Today in practice, is not required a retrospective explanation of the reasons for the created situation and their influence on the characteristics of this or that port, but what is usually necessary in applied theory: practical recommendations on the choice of development directions and establishment of limitations of its capabilities. The authors' article [6] presents a new formulation of the problem of synthesis of the structure of the sea passenger port, taking into account the functions and processes both for handling cruise ships and processes for handling passengers and accompanying cargo traffic in the port terminal.

Two major trends in the industry can now be accurately identified [8-11]:

1. Increase in the size of cruise and ferry liners, which requires modernization of the infrastructure. Let us explain this situation based on the passenger port of Saint Petersburg "Marine Façade" (St. Petersburg). The basic length of berths for cruise and ferry ships was determined based on models and in relation to the size of cruise ships in 2009 year. Today the situation is completely different. If the port does not change the infrastructure, will not perform actions to increase the length of berths the city, the region will lose passenger traffic, as more liners larger than 333 meters will not be able to berth.
2. Impact of digitalization processes, both on processing and on port services.

Despite the situation caused by COVID-19, there is still considerable public interest in cruise and ferry travel. Given the growing volume of passenger traffic [10, 11, 12], a modern sea passenger port must ensure high productivity, reliability and efficiency of passenger and related cargo handling, reduction of time for vessel handling processes in the port and uninterrupted operation of services and departments. This requires changes in the organization of processes and application of modern digital technologies.

It is necessary to consider the impact of modern digitalization processes [13, 14] and, as a consequence, the acceleration of processes. The transition to the digital economy implies the transformation of the development strategy and structure of the organization, for example, ports, ferry companies, services provided and organizational culture, which allows adapting to the digital needs of customers, to realize just in time their expectations, and as a consequence, to strengthen the competitive position in the market of services provided. The need for accelerated implementation of digital technologies in the economic and social sphere forms new tasks for the subjects of transport space. The transition to "digital" by the subjects of transport space will lead to both certain advantages and disadvantages. The transition of seaports to digital management is an important issue in the processes of globalization of production, increasing access to markets and effective integration into the global economy.

The advantages of using digital solutions are as follows:

1. new ways to save resources;
2. automation of business processes;
3. personalization for different categories of clients;
4. capability of detailed analysis and data collection for forecasting;
5. integration of digital processor models and systems into the work processes (as applied to the ports and terminals);
6. solving the problem of forecasting the development and reasonable modernization of infrastructure;
7. possibility to develop a specialized information system for each enterprise to collect data, to analyze and to solve the problem of forecasting of development; and
8. allows researching of the mutual influence of a city and a sea passenger port, enabling investigation of different strategies of a sea port behavior. However, there are significant disadvantages as well.

The disadvantages of using "digital" solutions are as follows:

1. The complexity of switching to dynamic models in the operation of the systems;

2. There appears to be some dependence on digitalization, collection of big data and analysis;
3. Possible technical failures in the operation of equipment and losses in data;
4. There are no universal solutions applicable to any seaport or terminal;
5. Difficulty of development and subsequent integration of digital transport models in the processes for each port; and
6. Digital models are needed for large ports and terminals.

To support the digitalization of ports, a logistics digital infrastructure is needed, the key elements of which are dedicated web-based logistics services that collect, display and distribute transportation requests; adaptive schedulers individually provided to logistics companies and organizations as web-oriented services and scheduling of passenger movements. Digital models of passenger seaports must provide accurate infrastructure implementation, obtain data from the operational level and allow for the task of forecasting development, taking into account the influence of the external environment. The use of digital models requires the use of Internet of Things-based models. Today, it is also necessary to use Internet of Things-based solutions to connect with logistics resources, including the connection between customers, orders, ships, ferry and cruise market participants.

2. MODELS AND METHODS OF FORECASTING THE DEVELOPMENT OF "CITY-SEAPORT PASSENGER PORT" SYSTEMS

As a result of changes in the global economy, including restrictions due to COVID-19, seaports have become subjects of competition in the world transport and logistics systems. This provision also directly applies to the seaports of passengers as major centers of development of cruise and ferry lines, cruise industry and transport processes. On the basis of the authors' works [3, 5, 6], it can be concluded that by the 1980s, it became obvious that without proper research and analysis of seaport development, it is impossible to manage, design and forecast sea development of passenger ports effectively. Forecasting of development is one of the key areas as it allows us to obtain answers to such questions as:
1. What changes should be made to port infrastructure to increase efficiency in processing cruise and ferry ships?
2. What changes in port infrastructure are necessary for operative processing of passenger traffic?
3. What strategy and decision-making system should be adopted to increase the number of cruise and ferry ships to make a difference in the sea region?
4. How many new berths or new technological port equipment need to be introduced?

In an effort to describe the patterns of port development, a number of static models of port development have been created. These models were based on observations and analytical calculation models. Their main disadvantage was the fact that in case of change of a certain parameter or process, it was necessary to recalculate the models. In addition, it should be said that such analytical models did not take into account the changing influence of new technological solutions. The solution turned out to be very limited and fair on a small time interval.

The following models of ports and terminals development are well known: Anyport, Model UNCTAD and Model Workport. Special attention should be paid to the authors Norcliffe G., Bassett K. and Hoare T. [15] , who proposed the study of ports and terminals development, taking into account the peculiarities of the geographical location of the port and considering the mutual influence of the port and the city. Let us apply elements of this model to sea passenger ports and terminals. This model is shown in Fig. 1.

Fig. 1 uses the following notation: *A* - set forming a sea passenger port; *B* - set forming a megapolis city; *C* - some new area formed by changing conditions of city–port interaction. Numbers I, II and III represent different models of the evolution of the relationship between the city and the ports.

In stage I, the city and the passenger port are part of each other, complement each other, are interested in active development and as a consequence, there is a balance of capacities. Over time, there is a transition to situation II. In this stage, the infrastructure of the seaport is preserved and there is significant urban sprawl, which leads to an imbalance in interests. A situation arises where the city needs a larger port, the need for infrastructural changes is seen, and the port infrastructure needs to be expanded. To solve this contradiction, the system must move to step III, when modernization is needed in the seaport of passengers, the modernization of the berth line C and the modernization of the hardware complexes of the terminal. In this case, the key process is highlighted - the number of berths. It should be noted that each stage I, II, III is characterized by the corresponding route network of ferry and cruise lines. The authors [16, 17] present the stages in the development of route networks, which correspond to the presented models and form a separate direction of research.

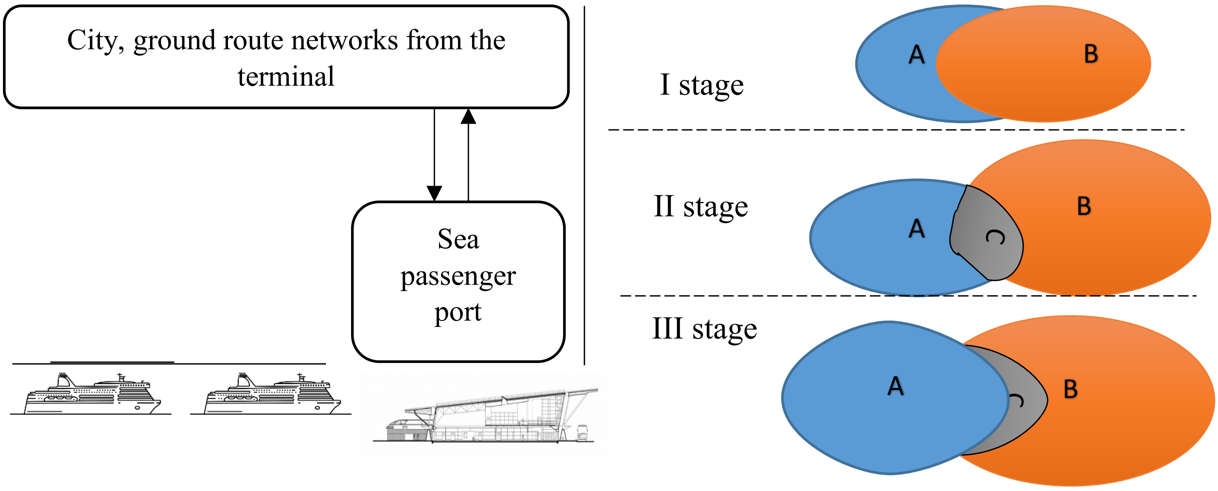

Fig. 1. Scheme of various stages of interaction between the systems «city - sea passenger port» using set theory

It is not enough only to use calculation models to justify the increase in the infrastructure of the sea passenger port. In this article, the use of a new digital transport model of the seaport of passengers is proposed for the analysis and forecasting of development. It is this model that opens up the possibility to investigate various options of infrastructure modernization and simulate scenarios. The proposed new solution was carried out in the laboratory of intelligent transport infrastructure of the department of system analysis and logistics SUAI.

3. INITIAL DATA FOR CREATION OF A DIGITAL MODEL OF THE SEA PASSENGER PORT

Marine Passenger Port of St. Petersburg "Sea Facade" (city of St. Petersburg) was chosen to carry out the study and forecast development [18]. Despite the current situation caused by restrictions due to COVID-19, the study requires statistics of the port operation over a long period of time. Now, when the restrictions are gradually being removed, the task of predicting the development and modernization of infrastructure, which will change the position of the port in the region, is extremely relevant. Based on the model shown in Fig. 1, it should be noted that in response to global trends, ports and terminals are increasing the number of berths and lengthening the existing ones to be able to accept larger ships. Otherwise, the region will lose passenger traffic, which will concentrate in another port of the region. Based on the raw data, the intensity of work since 2015 was analyzed. The results are presented in Table 1.

Fig. 2 shows the graphs of the functions of the seaport's work intensity by years. In the course of the study, the analysis of passenger port berth loading was performed and the specialization of berths according to the size of cruise and ferry ships was investigated. Initial data are necessary to check the correctness of the digital model and the correctness of mathematical models.

There were no calls to the port in 2020 because of restrictions due to COVID-19, so there are no statistics for this year. At the same time, the port creates new services and upgrades berth infrastructure. In 2021, berths 1.7 were modernized, which allows to accept cruise ships with lengths more than 333 meters. Since 2021, Passenger Port of Saint Petersburg "Marine Façade" has been expanding the line of services and opening its doors to serve the cargo flows [according to 18]. The port accepts all types of rolling cargo, equipment, optionally containerized and refrigerated cargo. The main operations include loading/unloading of cargoes, their temporary storage and surface processing of commodity lots.

Table 1
Intensities of cruise and ferry lines in the Passenger Port of Saint Petersburg "Marine Façade" (city of St. Petersburg) (number of units)

Year	Total number of ship calls / (number per month)	Year	Total number of ship calls / (number per month)	Year	Total number of ship calls / (number per month)
2015	230	2016	209	2017	249
January	0	January	0	January	0
February	0	February	0	February	0
March	0	March	0	March	0
April	0	April	0	April	0
May	35	May	36	May	42
June	54	June	44	June	57
July	60	July	61	July	68
August	54	August	45	August	56
September	22	September	20	September	21
October	4	October	3	October	5
November	0	November	0	November	0
December	1	December	0	December	0

Year	Total number of ship calls / (number per month)	Year	Total number of ship calls / (number per month)
2018	270	2019	265
January	0	January	0
February	0	February	0
March	0	March	0
April	1	April	1
May	47	May	47
June	63	June	54
July	54	July	68
August	65	August	58
September	34	September	31
October	7	October	7
November	0	November	0
December	0	December	0

To perform this task, the Passenger Port of Saint Petersburg "Marine Façade" uses two specialized berths, terminal tractors and other modern equipment for cargo handling. The total length of berths within the maritime frontiers is 2,212 m, which allows berthing of all types of ferry vessels with a maximum draft of 9.5 m. The cargo operations area includes berth 2, berth 3, automobile cargo front, open-air area with a possibility of one-time storage of up to 2500 vehicles, a modern indoor screening area, an unloading/loading and reloading area and a goods weighing area. In accordance with market standards, the introduction of a time-slotting system for entry to the terminal is planned, as well as electronic interaction with customers through a specialized web portal. The introduction of the new set of services was made possible by the implementation of a project under the «Russia-South-East Finland Cross-Border Cooperation Program» to reconstruct the checkpoint at the Passenger Port of St.

Petersburg to enable the use of the marine terminal infrastructure and the checkpoint for operations related to the reception of trucks transported by ferries.

To justify the forecasting of development and changes in the infrastructure of the sea passenger port, it is necessary to use modern digital models.

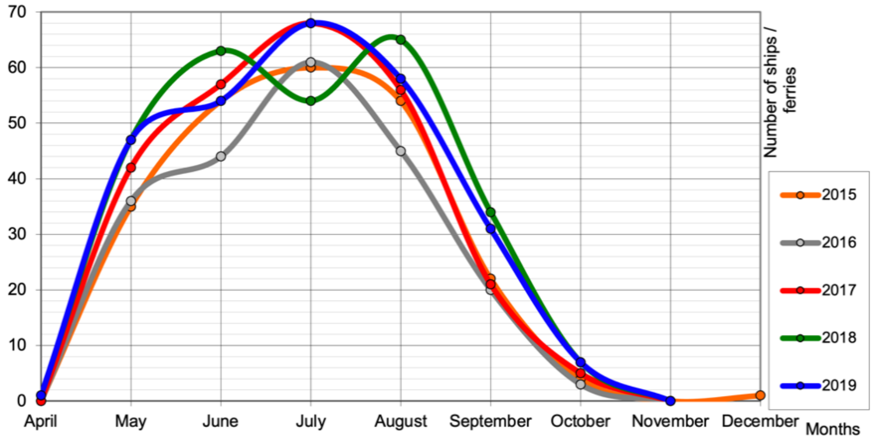

Fig. 2. Intensity of cruise and ferry ships calls at the Passenger Port of Saint Petersburg "Marine Façade"

4. PRACTICAL IMPLEMENTATION OF A DIGITAL MODEL OF A SEA PASSENGER PORT

The digital model of a sea passenger port should be as universal as possible, taking into account the real infrastructure of the selected port. According to the approaches of systems analysis [19], to implement this model, it is necessary to include both internal processes of the port and external processes and intensity of ship calls. The general scheme of building a digital model of the port is shown in Fig. 3.

The author's article [20] presents a solution to the problem of modeling passenger flows and determining the charge of the services of the selected seaport based on the known schedule of ship calls to the port. To study the modernization of berths and increase the intensity of work, it is necessary to build a model of ship calls. To solve the problem, the following approach was adopted. If cruise and ferry ships work on the line, the time of their call in the port is known with a certain accuracy, which indicates the presence of an aftereffect. Nevertheless, it does not exclude the action of adverse random factors, which can lead to a delay in the arrival of the vessel, as well as the possibility of relatively small deviations from the schedule of calls. In addition, if the passenger port is connected to the sea routes by an approach channel, the movement through which is specially regulated (for example, caravan traffic), this can also cause aftereffects. It can be taken into account by determining the interval between ship calls according to Erlang's law with the density of distribution.

$$f(t) = \frac{\lambda \cdot (\lambda t)^{r-1} e^{-\lambda t}}{(r-1)!}, \quad (1)$$

where $t \geq 0$ is the interval between vessel calls for a stream with aftereffects; λ is the intensity of the flow of cruise and ferry ships; and r is Erlang's order of distribution [21].

The greater the order of the Erlang distribution, the greater the consequence of the flow. When *r* = 1, the distribution is reduced to an exponential distribution.

The AnyLogic system [22] was chosen as the software tool. To implement the digital model, a professional version with all the libraries taken into account is required. In the chosen software environment, the possibility of connecting data from external sources, such as web services and work schedules, was implemented. The first step was to construct the port infrastructure in detail and specify the number of berths. Based on the data on ship calls and berth specialization, limitations were introduced into the model. On this basis, there are no errors in the model due to incorrect assignment of a berth to a cruise or ferry ship of large size. The Cruise Vessel Intensity Analysis Unit checks the vessels from the available database and assigns them a suitable berth. The next step was to integrate the seaport passenger handling processes presented in [14] and the intensity of ship calls to the port of the new model. After receiving a request to moor a ship to a berth, the internal passenger handling model is run. The window form of the implemented numerical model is shown in Fig. 4. When implementing the model, a 3D representation of the port model was implemented at the same time.

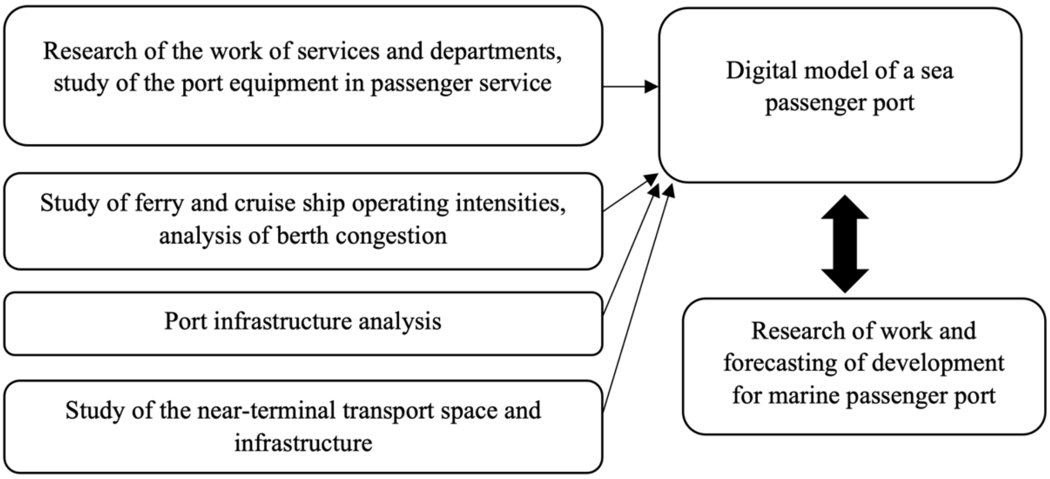

Fig. 3. Components of the transport model of the sea passenger port for the study of work, analysis and modernization of infrastructure, forecasting of development

Fig. 5 shows the data, which is a verification and confirms the correctness of the digital model. It should be noted that the implemented digital transport model requires a lot of computing power, as the processes of intensiveness of operation and maintenance of ships and internal processes of passenger flow processing are implemented simultaneously. Operational efficiency also depends on the speed of receiving data from external sources and work schedules. Data from external sources and databases can be added to the software system. The presented solution can be integrated for use with augmented reality systems, which opens up new practical applications of the developed digital model in practice.

5. CONCLUSION

Today, the use of new models, methods, tools for development forecasting is extremely relevant for sea passenger ports and terminals. The situation is especially relevant in connection with the processes of transport systems recovery after COVID-19. Seaports and terminals, which are new development centers in cities, must build up infrastructure and meet the new requirements of the industry. The use of analytical models is not enough, as their results are valid for a small interval of time. Today, it is also necessary to study the interaction of city–sea passenger port systems, as new requirements and new variables can only be learned by examining their mutual influence. This position is new and is currently described by models and methods of set theory. This paper presents three stages of seaport evolution, translates them to sea passenger ports and substantiates the use of new digital transport models. The uniqueness of these models is the combination of both external (ferry or cruise lines operation) and internal processes (passenger flow handling processes), taking into account the variables of external environment influence. The digital model of the port allows us to study the existing infrastructure, to substantiate the port modernization and also allows us to work with big data. As applied to task forecasting of sea passenger ports development on the basis of this model can be highlighted the following:

1. model adequately reflects port operation and is applicable for research of port development stages;
2. model reflects changes in the port's development with quantitative and qualitative changes in the intensity of both ship calls and passenger traffic handling;

3. model demonstrates acceleration or deceleration of port development with corresponding changes in cruise or ferry vessel intensities, or changes in passenger traffic; and
4. model is applicable to justify infrastructural changes.

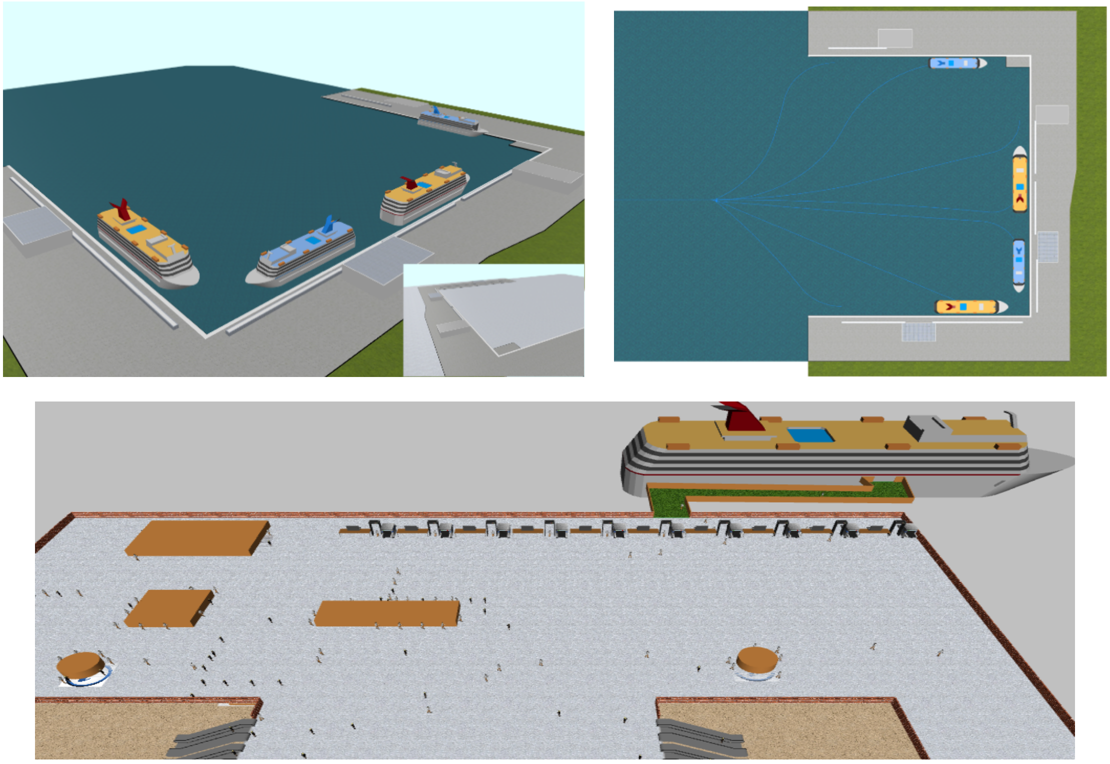

Fig. 4. Window forms of the digital transport model of the Passenger Port of Saint Petersburg "Marine Façade" (St. Petersburg), taking into account the intensity of vessel calls and passenger handling in the port terminals

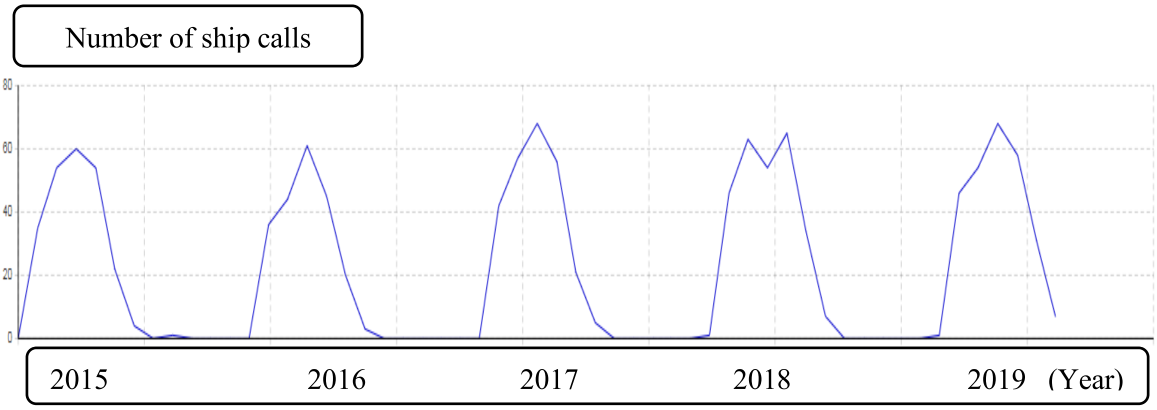

Fig. 5. The window form of the study of cruise and ferry ship intensity from 2015 to 2019 based on the connection to the digital model of data from an external source and the schedule of ship calls

Based on the initial data (presented in Fig. 2) and the practical simulation performed in a digital model, based on different distribution laws, a simulation result was obtained, which is confirmed by the original data on traffic intensity. On the basis of the correct model, it is possible to evaluate different variants of cruise and ferry ship intensities and to evaluate the possibility of infrastructure changes. On the basis of the correct digital simulation model, it provides the possibility to increase the accuracy of making and decisions on the modernization of the marine berth infrastructure and the evaluation of the loading capacity of the marine berth.

Based on the results obtained, we can say that modern digital models of passenger ports can answer a group of such important questions as changes in infrastructure, as well as forecasting of development and the study of port operation under different conditions. The presented solution is obtained for the Passenger Port of Saint Petersburg "Marine Façade" (St. Petersburg, Russia).

It should be noted that while the presented models have universality, for practical implementation, due to the peculiarities of each terminal, the development of individual models is required. This circumstance determines the complexity of development of such models and their integration into information systems. However, implementation of these models enables significant speed-up of decision-making and investigation of operational processes on a new level.

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