LogForum
> Scientific Journal of Logistics <
2022, 18 (3), 345-355
http://doi.org/10.17270/J.LOG.2022.745
http://www.logforum.net p-ISSN 1895-2038 e-ISSN 1734-459X
ORIGINAL PAPER

QUEUEING THEORY AS AN INSTRUMENT OF OPTIMIZATION OPERATIONAL AND ECONOMIC SPHERE OF PORT TERMINALS - CASE STUDY

Andrzej S. Grzelakowski, Adrianna Karaś

Gdynia Maritime University, Faculty of Management and Quality Science, **Poland**

ABSTRACT. Background: The maritime port terminals, handling cargo and servicing maritime and land means of transport with variable intensity over time, operate as mass service systems where the process of notifying and fulfilling needs usually occur at random. The main research problem was to determine the interdependence between the mechanism of reporting and meeting the demand for terminal services and its effectiveness measured in terms of operational efficiency and profitability.
Methods: The aim of research involves evaluating the terminal operational mechanism and evaluating it under operational categories, that is, operational stability and efficiency, and economic ones, i.e., effectiveness with respect to costs and revenue. To achieve the aim of research, the theory of mass service was applied, with the use of queuing theory as well as case study. The research was conducted in an example of bulk handling terminal, i.e. HES Gdynia Bulk Terminal.
Results: In the article, the authors assumed that the bulk cargo handling terminal in Gdynia operates as a queueing model. Therefore, it was possible to analyse the operating mechanism of the selected port terminal as a logistics system and a link in the supply chain by characterising it in terms of technical and operational efficiency and economic and financial effectiveness.
Conclusions: So far, such terminals have not the subject of this kind research, because researchers focused predominantly on seaports as composite multimodal transport nodes. The results of the conducted research confirm the previously formulated hypothesis, indicating that queueing theory can be used as an useful instrument to optimize the efficiency and effectiveness of bulk cargo terminals.

Keywords: port terminal, mass service system, queuing theory, terminal operating effectiveness, terminal efficiency, terminal added value

INTRODUCTION

Seaports as well as most port terminals that provide large-scale services for cargo and means of transport operate according to the principles typical of a mass service system. To some extent, this is an operating system characterized by the fact that the process of notification regarding the required services and the services provided occurs at random and usually with significant variability in time. It means that potentially at any time, depending on the terminal handling capacity, relative to the intensity and density of notification stream, namely the ratio between the load of this operating system at a given time and the intensity of notifications regarding services for ships or other means of transport, it may generate, within the entry subsystem, the waiting time, namely the queue [Jingjing and Dong 2012, Leon-Garcia 2008]. If the situation lasts longer, congestion is generated, indicating full congestion of the system and its inability to handle the notified requirements. It can be observed by the long queues and longer service gross time, i.e. the increase in the density of incoming notifications. In such a situation, the waiting time regarding ships' service can be n-times longer than the the time of actual cargo handling services at a berth [Deniz Özkan et al. 2022].

Citation: *Grzelakowski A. S., Karaś A., 2022. Queueing theory as an instrument of optimization operational and economic sphere of port terminals - case study. LogForum 18 (3), 345-355,* http://doi.org/10.17270/J.LOG.2021.745
Received: 20.07.2022, Accepted: 14.09.2022, on-line: 30.09.2022

The queue formation and the waiting time before entering the terminal as a mass service system generate additional costs for the terminal users [Layaa and Dullaert 2014]. They are the function of time necessary to wait for service in the system and consequently extended total gross time of meeting the requirements in the port terminal. In fact, these additional costs are real losses incurred by operators that use the services at such terminal. In view of the fact that the services of the terminal, which is an integral part of the global logistics supply chain, must meet the highest ecological and logistics standards, defined in the category of speed, safety, and reliability, as well as availability and mass quality, it means that the costs generated by the terminal will lead to an unjustified increase in the logistics costs within the supply chain, reducing the value created for the final user [Ruiz Estrada et al. 2017, Rudenko et al. 2022]. As a result, the terminal with such operating characteristics will gradually lose its share in partial markets, which will translate into its economic and financial position (EBITDA).

Ensuring the required efficiency and operational effectiveness, within the supply chain, as well as the economic effectiveness of a terminal of low standard with regard to meeting the notified requirements in the context of logistics (time and costs), and also as a mass service system always prone to generate queues of the means of transport waiting for services, which occurs, in particular, when there is no balance between the subsystem of notifications and the sub-system of provided services, requires taking investment-related as well as organizational and management-related actions. In this respect, particularly important is applying the model of port terminal management and implementing the strategy of its development based on the mathematical models developed under the theory of mass service and the queuing theory. Only in this way is the port terminal operator able to ensure efficiency and effectiveness of terminal operations, optimizing the unit costs of cargo handling services [Woo et al. 2011]. At the same time, such activities reduce the time and costs of services, generating an added value within the supply chain comprising the said terminal.

These matters and, in particular, issues related to the analysis of the notification stream related to ship service and services at the port bulk cargo handling terminal fall within the scope of research undertaken by the authors. The main issue and also the aim of research involves defining, under the queuing theory, the nature of the operational mechanism of the terminal as an operating system featuring mass services, and assessing the mechanism under operational categories, i.e., operational stability and efficiency as well as economic categories, i.e., effectiveness regarding costs and revenue, for the terminal operator and maritime transport operators.

The undertaken research is based on the assumption that at present, i.e., in the era of logistics development, smart supply chains and electronic business as well as large-scale implementation of operating solutions based on IT technologies (the era of digitalization), port terminals, including mass terminals of universal nature of operations, retain the previously developed operational characteristics which allow to classify them as mass service operating systems. Thus, the hypothesis formulated was verified in the framework of the conducted research process by applying mainly research methods such as queueing theory (QT) and case study (CS). The 2016–2019 study period was intentionally chosen to explore and present how terminals of this type operated in the pre-pandemic period. The following years, 2020-2022, as a result of numerous disruptions that occurred in both sea shipping and global supply chains at that time, fundamentally changed the previously existing model of servicing these terminals. The research covering this period will be presented by the authors in the next study in 2023. The key problem is to compare the two periods with each other.

The results and conclusions resulting from the analysis covering the years 2016-2019 were presented in part in the title Conclusion. Research was carried out at the example of universal port bulk cargo handling terminal, HES Gdynia Bulk Terminal. The article presents new content and results not yet published by other authors, pointing to the possibility of using the queuing theory instrument. This topic is rarely taken up in the context of mass terminals, and the attempts made relate to ships calling regularly at ports.

HES Gdynia Bulk Terminal is located at the main entrance to the Port of Gdynia (Fig. 1.). It is integrated into its facilities by road and rail transport. In its offer, the terminal provides 24h cargo handling services for dry bulk cargo (coal, coke, ores, grain, fodder, aggregates, ground grain), liquid (chemicals, liquid fuel) and general cargo. HES terminal provides 225 714 m^3 storage area in warehouses and 106 852 m^2 of yard space. The terminal is spreading along five quays. Liquid cargo handling includes dangerous cargo of 3, 6, 8 and 9 class chemicals under the IMDG code. The Duńskie Quay is equipped with tanker service berth of up to 210 meters in length and up to 11 meters of draught. The dry bulk cargo handling is provided in a four-chamber warehouse with loading and unloading system, located at the Śląskie Quay. The warehouse is intended to store products of ca. 60,000 tons of total mass. It is also connected through a conveyor belt system with a warehouse located at the Szwedzkie Quay of about. 40,000 tons of storage capacity.

HES Gdynia Bulk Terminal is part of the HES International capital group with affiliated companies.

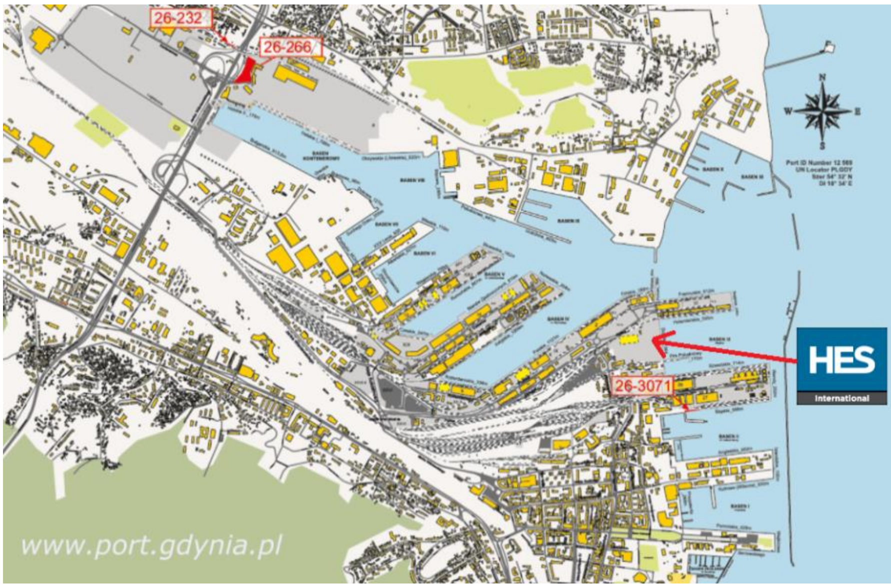

Fig. 1. Location of HES terminal on the map of the Port of Gdynia. Source: [www.port.gdynia.pl].

HES GDYNIA BULK TERMINAL AS A MASS SERVICE SYSTEM

- The calculations were based on data obtained from HES Gdynia Bulk Terminal, which, however, only to some extent allowed to consider how the terminal operates as a mass service system.
- The analysis covers the Szwedzkie Quay, the Śląskie Quay, the Holenderskie Quay, the Duńskie Quay and the Breakwater.
- The number of bulk carrier calls at the terminal in 2019 is 242 ships.
- In the first quarter of 2019, (I-III), the number of calls to the terminal totalled 61. In the second quarter (IV-VI), the number of ships totaled 61. In the third quarter (VII-IX), the number increased to 77, whereas in the fourth quarter (X-XII) the number of ships amounted to 63. In the first, second, as well as the third and fourth quarters, the frequency of ship calls is similar.
- The average deadweight tonnage (DWT) of a ship that landed at the HES terminal in 2019 totaled 40791 t. As many as 37 Capesize ships called at the terminal, as well as 15 Handy ships,, 31 Handymax ships and 23 Panamax ships (Fig. 3.).

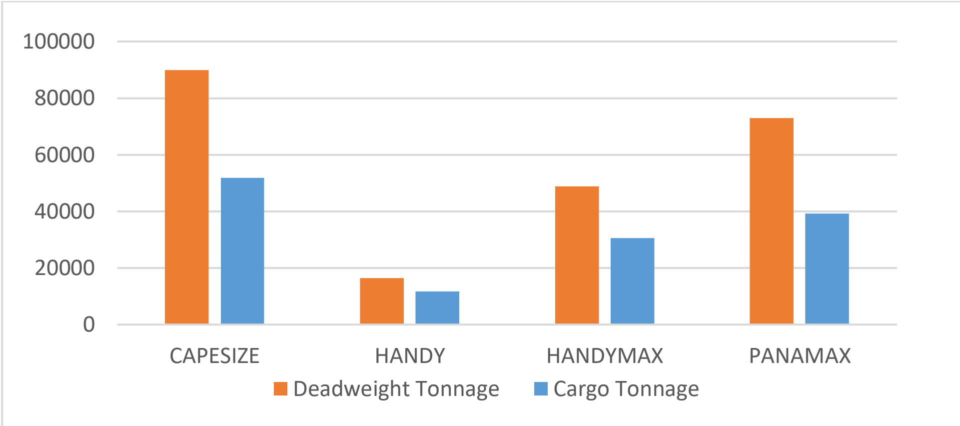

Fig. 3. Average deadweight tonnage and average cargo tonnage of ships calling at HES Gdynia Bulk Terminal.
Source: own work.

- The average ship service time is understood as the ship's time at berth until the reloading operations are complete.
- The average service time totals 48 h for 242 ships that arrive at the terminal in a year.
- Due to the lack of an access barrier to the terminal (no queue) $t_0=0$
- On average, ships arrive at the terminal every 34 h, which indicates an intensive notification stream (Fig. 4.). Server utilization totals ρ=0.71, which indicates significant use of the terminal while maintaining system stability.
-

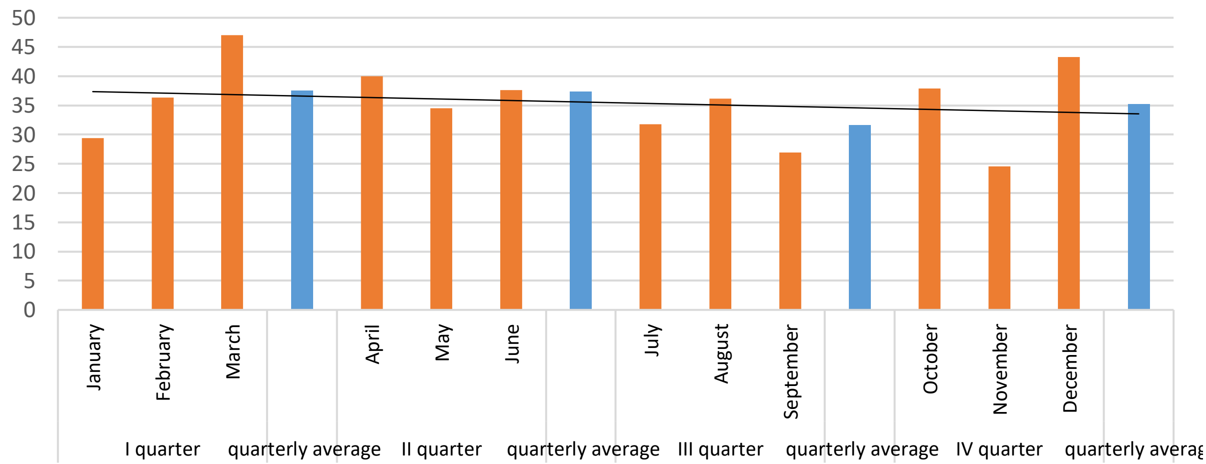

Fig. 4. Average time between ships' arrivals to the HES terminal in a given month.
Source: own work.

QUEUING MODEL OF THE PORT BULK CARGO UNLOADING TERMINAL IN GDYNIA

The statistical data of HES Bulk Terminal Gdynia show that the arrival rate of cargo λ totals 6 075 346 tons for the year of 2019 Eq.(3). In practice, the daily side handling rate (terminal handling capacity) means servicing 3 Panamax ships, 1 Handy ship, and 1 tanker at the same time. The data provided by the terminal prove that the average berth occupancy totals 50.34%; therefore, for the purpose of further calculations, it was assumed that the terminal handling rate totals 11,000,000 tons/year Eq. (4).

The parameters for the observed model include [Hess et al. 2007]:

- cargo arrival rate

λ = 6 075 346.1 t/year (1)

- cargo service rate

μ = 11 000 000 t/year (2)

The indices of unloading bulk cargo terminal operation are computed according to the appropriate queuing theory formula [Bose 2002, El-Naggar 2010]:

- traffic rate

$\rho = \lambda/\mu = 0.5522$ (3)

- the probability that there is no ship/cargo at the terminal, i.e., the berth is unoccupied

$p_0 = (1 - \rho) = 0.4478$ (4)

- the average quantity of cargo in queue

$L_q = \rho^2/1 - \rho = 0.6810$ t (5)

- the average amount of cargo at the terminal (in queue and being serviced)

$L = \lambda/\mu - \lambda = \rho/1 - \rho = 1.2330$ t (6)

- the average amount of cargo which is just being serviced

$L_{serv} = L - L_Q = \rho = 0.5522$ t (7)

- the average queuing time of cargo, that is, the queuing time of cargo prior to being serviced

$W_Q = L_Q/\lambda = 0.9811$h/1000 t (8)

- the average time of cargo's stay at the terminal, i.e., queuing time of cargo and duration of its unloading

$W = L/\lambda = 1.7782$h/1000 t (9)

- the average duration of cargo service-cargo unloading

$W_{serv} = W - W_Q = 0.7971$h/1000 t (10)

Table. 1. Unloading terminal operation indices for years 2016 and 2019.

Indices	Unit	2016	2017	2018	2019
ships	number	256	219	249	242
λ	ton/year	4 011 179.5	5 356 291.6	6 006 161.9	6 075 346.1
μ	ton/year	11 000 000	11 000 000	11 000 000	11 000 000
ρ	-	0.3646	0.4869	0.5460	0.5523
p_0	-	0.6353	0.5130	0.4540	0.4477
L_Q	ton	0.2092	0.4621	0.6566	0.6813
L	ton	0.5739	0.9491	1.2026	1.2336
L_{serv}	ton	0.3646	0.4869	0.5460	0.5523
W_Q	hour/1000 tons	0.4569	0.7557	0.9577	0.9824
W	hour/1000 tons	1.2533	1.5522	1.7540	1.7787
W_{serv}	hour/1000 tons	0.7964	0.7965	0.7963	0.7963

Source: own work.

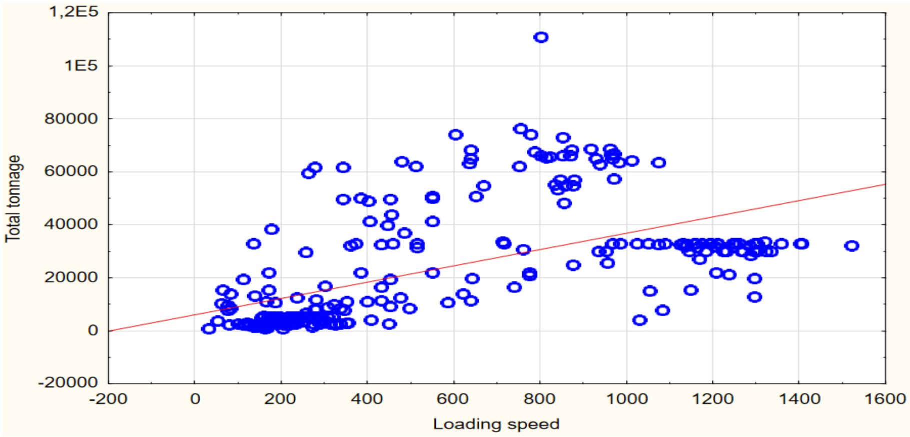

Fig. 5. Average loading speed scatterplot – 2019 year.
Source: own work.

It can be seen that in 2019 the cargo arrival rate in relation to cargo service rate, traffic rate ρ is 55% Eq. (5), and the probability that the berth is unoccupied amounts to 45% Eq. (6). Furthermore, the scatterplot shows that the larger the vessel, the faster the loading. However, the average handling speed totals 556.19 ton/h and does not depend on seasonality and external factors, since in the first quarter of 2019 the average handling speed totalled 555.28 ton/h, in the second quarter – 533.17 ton/h, in the third quarter – 515.13 ton/h, and in the fourth quarter – 609.19 ton/h (Fig. 5). The fastest cargo handled at the terminal is diesel oil; the loading speed is 1093.84 ton/h. The largest number of ships serviced at the terminal include ships carrying soybean meal (58 ships) and diesel oil (64 ships).

TERMINAL OPERATIONAL EFFICIENCY AND ITS ECONOMIC AND FINANCIAL RESULTS

The conducted analysis of HES terminal operation as a mass service system indicates that at the current level of cargo handling capacity and the existing intensity and density of the notification stream, it fails to generate the waiting time for service in the entry subsystem. The gross time of the ship's stay in the port is determined in these conditions practically exclusively by the actual time of the ship's service at the terminal. The time comprises the time of handling operations at the berth and the preparatory and completion procedures.

It means that within the current operational conditions:

1. the terminal is characterized by high operational efficiency measured by the time of service for all types of bulk cargo ships, notified in advance by the shipowners' agents making use of the terminal services,
2. the shipowners whose ships enter the terminal do not actually incur any indirect costs, being the function of service awaiting time.

Therefore, during the research period, the maritime transport operators fell within a group of beneficiaries of such a market system based on the relationship between the effective demand defining the notification stream and its distribution in time and the potential supply of terminal services, determined by cargo handling capacity of all berths. Consequently:

– the total terminal costs that constitute a significant component of port-related costs of the shipping operators who make use of the services provided by the HES terminal in Gdynia, as well as their
– unit costs calculated per 1 ton of cargo tonnage carried on the ship's side or 1dwt, or GT, between 2016 and 2019, at the average berth occupancy of 51 % (whereas realistically 46.5 % - 53.1 % - compare Fig. 6), were relatively very low. Since they were determined only by the level of fees for the loading and unloading operations and other related services at the terminal and in the port in Gdynia.

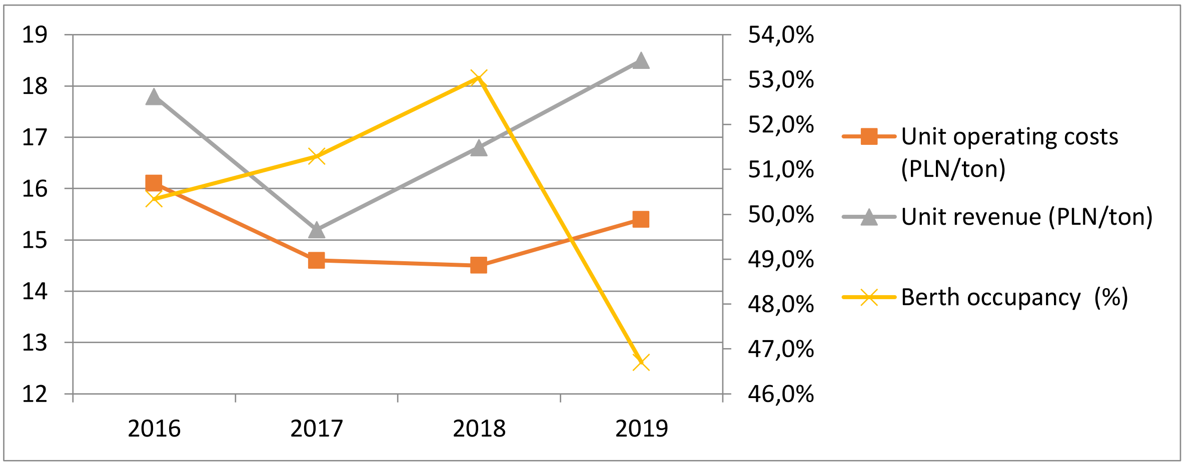

Fig. 6. The unit operating costs and unit revenue from basic operating activity of the terminal (in PLN/ton) between 2016 and 2019, in the function of average berth occupancy between these years (in %).
Source: own work.

This mechanism of completing the ship service processes ensured by the HES terminal, as a mass service system related to meeting the notified requirements of maritime transport operators, with respect to loading and unloading services, characterised by high operational and logistics efficiency, generated specific results for the terminal and maritime operators. By evaluating these results through the economic criteria, it can be concluded that in such conditions, we could observe the transfer of added value generated by the terminal to the shipping sector, that is, a group of shipping operators who used the terminal services. This situation, typical of mass service systems, the entry subsystems of which do not generate queues and over-congestion, reflects one of the possible forms of added value of transfer between two „maritime" links of the international logistics supply chain.

However, at the same time, during the studies, the terminal operator, as another entity within the supply chain, effectively implemented its own management strategy of the ship handling processes, meeting the handling requirements notified by the shippers and shipping operators, and the related transport processes smoothly and effectively. The average costs of its operational activity in the period analysed (in PLN/ton) were relatively stable, fluctuating between 14.4 and 16.1 PLN/t. (Fig. 6.) However, it is also characteristic that if the rate of change related to these costs is assessed as average values for each year, a clear regularity can be observed between the level of terminal unit operating costs and the average level of using the handling potential at berths (Fig. 6.). This cause-and-effect relationship measured by the correlation between these two factors, which define directly and indirectly the operational efficiency and economic effectiveness of the terminal, as a mass service system, was, as expected, inversely proportional (negative correlation).

It meant that:

1. the level of average terminal operating costs mainly determines the fixed costs, regardless of the variables within the conditions of the handling process, and in the structure of these costs relatively low is the share of depreciation costs of fixed assets involved in the process; moreover, the costs are calculated under linear method, i.e., fixed write-off rate on an annual basis,
2. in such a situation, the number of serviced ships, namely the intensity and density of the notification stream and the volume of handled cargo tonnage at the terminal not only translates into the level of berth occupancy, but also exerts significant impact on developing the level of unit operating costs of the cargo handling terminal; with the increase in berth occupancy, i.e. the load of the terminal as a mass service system, we

could observe the degression of these costs or their increase, when the berth occupancy indicator was going down, as in 2019,

3. the rate of change in the level of unit operating costs relative to, variable at that time, berth occupancy indicator reflected in the accounting system with some delay in time (since these are average annual values) was to a larger extent dependent on: a/ the volume of cargo tonnage handled at the terminal berths than on the number of ships and b/ the level of fixed costs degression with the increasing load of the system than on the increase in variable costs.

In such conditions, the terminal as an operating system as characterised above could implement, with a high probability of success, the strategy based on the business model focused on achieving the optimal level of technical production, aiming to minimize the average unit operating costs of the performed cargo handling operations. These min. costs are obtained at such a level of production measured with the berth occupancy indicator when the curve of these costs crosses the curve of short-term marginal costs.

The costs of terminal basic operating activity participated in the analysed period on average at ca. 88% in revenue from the sale of services, falling between 91 and 83%, although from 2017, we could observe a steady declining tendency of the share of these costs in the value of generated revenue. It means that these costs represented: 1/ the main component defining the level of revenue generated by the terminal managing company and 2/ determined to the largest extent the level of profitability of the conducted operating activity. This profitability, in turn, in the absolute and unit-related dimensions, was determined by the rate of changes in the level of costs and revenue. However, as long as unit operating costs increased only and slightly in 2019 compared to 2018 (the lowest level at that time), unit revenue was characterized by a relatively high growth rate from 2017 (Fig. 6.). As a result, the unit cargo handling profitability (1 ton of cargo) showed an increasing tendency.

The analysis of these relations in the context of costs – revenue, both total and unit costs of the terminal perceived in the framework of average level of using the berth cargo handling potential (Fig. 6.), indicates that:

1. unit operating revenue, which being the function of the price level for the handling of cargo and other services of the terminal, and the volume of cargo tonnage handled in this transport system always remained on a higher level than the costs of such activity, and the rate and direction of changes in the analysed period reflected, to a large extent, the tendencies regarding changes in unit operating costs (positive correlation),
2. however, from 2017, the total revenue of the terminal management company and its unit operating revenue increased faster than the costs of this activity, developing to a large extent regardless of its level of, which probably resulting mainly from the increase in fees for cargo handling services and a more significant degression of unit fixed costs relative to the increase in unit variable costs at the same level of berth occupancy,
3. however, this detachment of terminal revenue from the basis of its operating costs, increasing gradually from 2017, namely some sort of ‘shears opening’ visible in the analysis of these financial parameters per unit (Fig. 6.), fails to correlate – in particular in revenue - with the cargo handling activity of the terminal as a mass service system, measured by the average use of the berth cargo handling potential; nevertheless, this could involve changes in the size structure of ships serviced at berths – their deadweight and tonnage and volume of cargo loaded and unloaded at the terminal,
4. the trend was particularly visible from 2018, in the context of unit revenue of the cargo handling company relative to the level of berth occupancy, which did not occur in the entire analysed period when the growth rate of revenue per unit closely correlated with the growth rate of berth occupancy (strong positive correlation at 85 %).

The conducted analysis of unit costs and basic operating revenue of the HES terminal in the function of using the cargo handling capacity of its berths indicates that the terminal as a logistics system and a link in the supply chain operated in the analysed period:

1. efficiently not only in the logistics categories, servicing ships and meeting the notified cargo handling requirements with high technical and operational efficiency, and also in a safe and reliable manner.
2. effectively in both financial and economic categories, generating:

   a. significant revenue per unit in the operating activity and gross profit within the conducted basic activity (financial results),
   b. high added value thanks to the possibility to reduce fixed costs because of the technologically and economically optimal use of the cargo handling potential, measured by the berth occupancy indicator.

CONCLUSION

To analyse the processes within the terminal, queuing theory was applied, as one of the research methods verifying the service processes. In the article, the authors assumed that the bulk cargo handling terminal in Gdynia operates as a queueing model. Therefore, it was possible to analyze the operating mechanism of the selected port terminal as a logistics system and a link in the supply chain by characterising it in terms of technical and operational efficiency and economic and financial effectiveness, as well as logistics efficiency [Merk and Dang 2012], [Ye et al. 2020]. By applying the mass service theory, based on the conducted statistical analysis of data, it was possible to determine the character of the stream of notifications from ships calling at the HES terminal, on a monthly and annual basis, identifying in the analysed period its intensity and density, i.e., the number of entries into the subsystem per unit of time and their distribution in time, and the mechanism of handling these notifications at the terminal as a mass service system. The results of conducted research indicate that

1. there is no significant correlation between the number of ships' calls and the time of their service at the terminal; since there was no waiting time for entry into the system in the analysed period of time,
2. the sub-system of ship services in the context of logistics efficiency operated effectively, which indicated that it was adjusted in the technical and operational aspects (cargo handling capacity in terminal berths, berth occupancy in time) to the stochastically defined entry subsystem requirements, determined by the character of ships' notification stream distribution,
3. the absence of waiting time for ship service meant that the gross time of the stay in the port was solely defined by the actual time of service at the terminal, which indicates that under such conditions we could observe the actual transfer of added value generated by the terminal operator to the group of shipping operators who made use of the services provided,
4. the shipping operators using the services of the terminal as a mass service system were included in a group of main beneficiaries, and the scale of their benefits define by the savings in gross time of ship's service in the port determined the level of daily charter rate,
5. on average the terminal achieved a relatively high level of cargo handling potential use, measured by the berth occupancy indicator, which provided its operator with the possibility to obtain significant reductions in the unit fixed costs, being the main component of business operating costs;
6. in such conditions, in the analysed period, by obtaining regular surplus in operating revenue over the costs of operations (increase in handling profitability per unit), the terminal operator could implement the operating strategy focused on achieving the optimum of the technological production,
7. as a result of gradual detachment of the terminal operating revenue (high growth rate) from the basis of its operating costs, the level of which as unit costs was correlated in general with the cargo

handling activity of the terminal as a mass service system, measured by the average level of utilizing its berth cargo handling potential, such a tendency cannot be observed to the same extent at the terminal revenue per unit; the correlation in this respect is subject to significant change in time, which indicates that it is determined by many other factors, not included in the analysis,

8. the current state of relative balance between the entry subsystem and the sub-system of notification handling at the terminal as a mass service system, as well as the scale of generated benefits, fail to provide grounds for making in the nearest future large-scale investments, leading to increasing the terminal cargo handling capacity, and only at the very most, modernizations and purchase of fixed assets within intangible assets.

In conclusion, it can be determined that in the era of the logistics supply chain development and mass implementation of digital technologies, seaports and port terminals and not only the container terminals, by maintaining the character of operating systems typical of mass service systems operate equally efficiently and effectively in the supply chain system as its other entities, generating no additional logistics costs being the function of cargo handling service time. Instead, they have the possibility to generate added value, which is sometimes transferred in large part to other entities in the global value chain.

ACKNOWLEDGMENTS

This research was supported as far as access of necessary data was concerned by the HES Gdynia Bulk Terminal. We would like to thank CEO of the above mentioned company and its Head of the Accounting Department. The study was carried out within the Gdynia Maritime University grant WZNJ/20221/PZ/06.

REFERENCES

Bose S. J., 2002, An Introduction to Queuing Systems, Springer, 17-20, https://doi.org/10.1007/978-1-4615-0001-8

Deniz Özkan E., Koçer U. U., Nas S., İşlek Ö., Tüzgen E., Doğan, A., 2022, A simulation model for evaluating the cargo transfer alternatives in liquid cargo terminals, Simulation, https://doi.org/10.1177/00375497221107938.

El-Naggar M.E., 2010, Application of queuing theory to the container terminal at Alexandria seaport, 77-85.

Hess M., Kos S., Hess S., 2007, Queueing System in Optimization Function of Port's Bulk Unloading Terminal. Science in Traffic and Transport, 2, 67-70, https://doaj.org/article/9f5703292d244f5d945c9d6e18ac2c65

Jingjing X., Dong L., 2012, Queuing Models to Improve Port Terminal Handling Service, Systems Engineering Procedia, 4, 345 – 351, https://doi.org/10.1016/j.sepro.2011.11.085

Layaa J., Dullaert W., 2014, Measuring and analysing terminal capacity in East Africa: The case of the seaport of Dar es Salaam. Maritime Economics & Logistics, 16, 141–164, https://doi.org/10.1057/mel.2013.23

Leon-Garcia A., 2008, Probability, Statistics, and Random Processes for Electrical Engineering, Pearson Education, 3, 714-715.

Main website HES Gdynia Bulk Terminal, Available on the Internet: https://www.hesinternational.eu/pl/terminale/hes-gdynia (10/15/2021).

Main website Port of Gdynia Authority SA., Available on the Internet: https://www.port.gdynia.pl/ (12/10/2021).

Merk O., Dang T., 2012, Efficiency of world ports in container and bulk cargo (oil, coal, ores and grain), OECD Regional Development Working Papers, 9, 28.

Rudenko S., Shakhov A., Lapkina I., Shumylo O., Malaksiano M., Horchynskyi I., 2022, Multicriteria approach to determining the optimal composition of technical means in the design of sea grain terminals. Transactions on Maritime Science, 11(1), 28-44, https://www.toms.com.hr/index.php/toms/article/view/475

Ruiz Estrada M. A., Salarzadeh Jenatabadi H., Chin, A.T.H., 2017, Measuring Ports Efficiency under the Application of PEP-Model, Procedia Computer Science, 104, 205-212, https://doi.org/10.1016/j.procs.2017.01.107

Woo S.H., Pettit S., Beresford A.K., 2011, Port evolution and performance in changing logistics environments. Maritime Economics & Logistics, 13, 250-277, https://doi.org/10.1057/mel.2011.12

Ye S., Qi X., Xu Y., 2020, Analyzing the relative efficiency of China's Yangtze River port system, Maritime Economics & Logistics, 22, 640–660, https://doi.org/10.1057/s41278-020-00148-5

Andrzej S. Grzelakowski ORCID ID: https://orcid.org/0000-001-7190-6115
Gdynia Maritime University,
Faculty of Management and Quality Science,
Department of Logistics and Transport Systems, Gdynia, **Poland**
e-mail: a.grzelakowski@wznj.umg.edu.pl

Adrianna Karaś ORCID ID:https://orcid.org/0000-0002-9036-4419
Gdynia Maritime University,
Faculty of Management and Quality Science,
Department of Logistics and Transport Systems, Gdynia, **Poland**
e-mail: a.karas@wznj.umg.edu.pl