Solutions for the port facilities development

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Abstract. The development of the port facilities must be carried out in concordance with the ships flows size so that the sum of waiting costs for demands arrived for service and also for the service stations is minimal. In actual operating conditions this minimum is difficult to obtain due to varying demands faced by ports. The solutions for the port facilities’ development are based on the criterion that aims maximizing the social benefit obtained using the mathematical models of queuing theory. The paper aims to identify models for developing port facilities’ by which a rational dimensioning of installations subjected to time variable demands will be achieved (handling facilities at berth, covered / uncovered storage areas). Considering the multitude of mathematical models of the differentiated queuing theory according to the number of channels, distribution of arrival times and distribution of service time or the number of places in the waiting string / system, there is a problem of choosing the model to approximate as accurately as possible the future operation of the port system. The model validation is done through a case study which solve a problem of rational development of the necessary port facilities at an operational berth. The proposed model use the minimum economic cost criterion (cost of ships waiting for service and cost of berth inactivity) knowing that the ratio of these costs in most cases exceeds 4/1.

1. General considerations
The optimal sizing, developing and exploitation of the port facilities problems have always been subjects of many technical papers due to its difficulty stemming from the multitude of factors, parameters, operating hypotheses, restrictions and connections involve [1-4].

The port is a typical example of an intermodal terminal in which, for the smooth running of the transport process the following conditions must be met: the transport process continuity, the accordance of transfer and storage capacities, a logical succession of system occupancy times in the technological flow, [5]. The simultaneous fulfilment of these conditions becomes difficult, mainly due to exogenous factors of the port system (weather conditions, different ship capacities and capabilities, international political situation) leading to variable exploitation demands of the installations. This tend to disturb the rhythm of land transport thus transferring congestion to another area or transport terminal.

The variable demands in port operation are undesirable as they lead to the maintenance of additional capacities that are only used during peak periods of traffic, so investments for additional technical endowments are not recovered[6]. It follows that it’s being searched the criterion on which to determine the optimal structure of port technical endowments is sought. The criterion is adopted according to the interests of the decision-maker but in many technical papers [5, 4, 11, 15] it is mentioned as an economic criterion.
Specific models for the sizing and development of port facilities have been developed using the principle of maximizing the social benefit. An economically correct sizing can be achieved by using the mathematical models of mass-service waiting theory where ships are system users waiting for service and service stations may be berths or handling facilities on the quay [12-14].

There are a multitude of mathematical models of the queuing theory, differentiated by the time arrivals distribution or time service distribution, the number of serving stations, the serving discipline, or the number of places in the queue/string. Thus, it appears the problem of choosing a model that approximates more accurately the operation of the port system. [15].

It is also emphasized that models that do not use elementary flows (Poisson distribution of arrival times) lead to complicated and difficult to use mathematical expressions, which limits the scope of applicability of the models.

The mathematical theory of mass service allows the processing and interpretation of waiting issues so as to improve their negative effect and at the same time offers the possibility to make predictions on which to achieve optimal operation of the port system in terms of cost.

The issue of optimal sizing is not so simple for berths where ships loading/unloading is carried out with intermediate storage (indirect transfer). However, by introducing some simplifying assumptions, the operation of such a transfer system can be assimilated with two series-connected waiting systems. (Problems arise in harmonizing the processing capacity of the two systems, since capacity constraints may come from either of the two interconnected systems) [14].

When using the multichannel direct transfer model (with multiple serving stations working in parallel), it can be noticed that the average waiting time for service decreases if the average arrivals intensity and average service intensity increases to the same extent. So, for high-capacity installations, higher demands can be accepted [6,7].

$$\rho = \frac{\lambda}{\mu} = \tilde{t}_m; \quad \rho = \lambda_1 \tilde{t}_{n1} = \lambda_2 \tilde{t}_{n2}. \quad (1)$$

If $\tilde{t}_{n1} < \tilde{t}_{n2} \Rightarrow \lambda_1 > \lambda_2$,

where $\lambda, \mu$ represent the average arrivals intensity and the average service intensity;

$\rho$ – the service intensity factor of the system or the number of demands arriving in the system while an unit is in service;

$\tilde{t}_m$ – the average time of serving a demand.

The values of the service intensity factor according to the number of installations of the same type, taking into consideration a ratio between the cost for ship operation and the cost for of port installations operation of 4/1, are presented in the table 1.

**Table 1. Recommended values of the service intensity factor [10].**

| The number of the same type installations | 1     | 2     | 3     | 4     | 5     | 6 – 10 |
|-----------------------------------------|-------|-------|-------|-------|-------|--------|
| Service intensity factor                | 0.4   | 0.5   | 0.55  | 0.6   | 0.65  | 0.7    |

As can be seen from Table 1, for small numbers of installations also the service intensity factor is low, this translates into a high degree of inactivity, which in many cases is not accepted by the port administrations.

Problems arise when analyzing multi-channel serving models if the port has a single dock with successive berths because the number of serving stations can not be determined rigorously. One hypothesis would be that a berth be defined by a certain quay length so that a representative type of ship could be accommodated and the number of berths will be given by the number of ships that could be hauled simultaneously along the quay. This hypothesis is not always suitable because in the case of container terminals, the transtainer cranes are considered as service stations because they determine
the area where service can be done. If the quay is fully occupied by the ships, the number of cranes may be insufficient to serve all moored ships and therefore the definition of berths according to their length is inappropriate. In other cases ships with self-handling facilities may be moored, in which case the number of berths can be defined according to the length of the quay.

The question arises: how many cranes are in a serving station? It is assumed that there are cranes that can be used simultaneously for a ship and that the marginal productivity of the cranes is constant regardless of whether they work for the same ship or for different ships. Under these circumstances, for a system consisting of 3 cranes, it is considered that the total waiting time in the system is minimal if all cranes are used for a single ship. [10]. So the distribution of cranes by a crane for each of the three ships, two cranes for a ship and one crane for another ship is disadvantageous.

For clarification, it is assumed that three identical ships arrive at the same time in the port and that service time will be one day if 3 cranes are allocated to a ship, 1.5 days if 2 cranes are allocated to a ship and 3 days if one crane is allocated to each ship. The solution is presented in table 2.

Table 2. The total time in the system [14].

| Allocation of cranes | Total service time [days] | Total waiting time [days] | Total waiting time in the system [days] |
|----------------------|---------------------------|---------------------------|----------------------------------------|
| 3 0 0                | 1 + 1 + 1                 | 0 + 1 + 2                 | 6,0                                    |
| 2 1 0                | 2 × 1,5 + 1 × 3           | 0 + 0 + 1,5               | 7,5                                    |
| 1 1 1                | 3 × 3                     | 0                         | 9,0                                    |

Table 2 shows that the most efficient policy is to allocate all three cranes to operate on each ship.

2. Models based on minimizing the waiting costs
The problem of reducing the waiting time of vessels in ports is of particular economic importance, due to the need to reduce or even eliminate demurrage resulting from failure of the operation times provided in the charter contracts.

The use of the multimodal direct transfer model for port equipment sizing aims to optimize some functions or system parameters. In this sense, we try to optimize the economic function of the system, which is the sum of the waiting costs, both on the part of the ships arriving for operation and on the port installations (often there are restrictions in addition to the economic function).

Port installation costs consist of:

a) a quasi-fixed cost comprising the equipment of the quay, warehouses, cranes, etc.,
b) a variable cost comprising handling costs, fuel cost, taxes of various kinds.

Their variation is shown in the figure 1, [10]

When the traffic volume increase, the quasi-fix cost decrease, while the variable cost remains constant until the port installations have to meet a higher traffic volume. At this point it tends to grow because more expensive handling methods must be used.

The cost of ships waiting time in the port also has two components (figure 2):

a) the cost of operating time (the waiting time at berth),
b) the cost of waiting for operation at berth. As traffic increases, the cost of waiting times increases greatly, even exponentially.

The total cost is the sum of the port facilities cost and the cost of ships waiting time in the port. These are shown in figure 3. It is shown in figure 3 that the graph representing the total cost for port system curve has a minimum in point B. This minimum is at a traffic volume lower than the minimum cost for port facilities (point A). If port planning / sizing only takes into account the minimization of port facilities cost, the quantity and quality of services provided to shipowners will decrease which will lead to to port congestion and implicitly entail additional costs and economic inacceptability. The size of the various cost elements, determines ways to reduce total port costs. The minimum amount of
these costs depends on the ratio of the specific ships waiting time in port’ cost and port facilities’ cost, which has common values of $4/1$ [10].

**Figure 1.** Variation of port installation costs.

**Figure 2.** The cost of ships waiting time in the port.

The form of the total cost curve and its minimum is determined by the complex mathematical relationships that exist in the queuing theory for the average waiting and serving times. The optimal solution is obtained by calculating the numerical value of the function $F(s)$, for different numbers of berths $(s)$. In most cases, this function is expressed as the statistical mean of waiting time costs (ships and berths waiting times) over a time period $T$ [16]:

$$F(s) = (c_1 \bar{n}_a + c_2 \bar{\Phi}) T = \left[ c_1 \bar{X} + c_2 (s - \rho) \right] T,$$

where $c_1$ is the time unit cost for waiting demand;

$\bar{n}_a$ - average number of units within the queue;

$\bar{\Phi}$ - average number of unoccupied stations;

$c_2$ – time unit cost for service stations downtimes;
\( \lambda \) - average arrivals intensity;
\( \mu \) - average service intensity;
\( t_a \) - average queue waiting time.

![Figure 3. The variation of the total cost for port system.](image-url)

Within \( F(s) \), \( \rho \) and \( t_a \) must be determined. The value \( \rho \) is quite simple to be determined, while \( t_a \) requires thorough calculation and a comprehensive study of the waiting phenomenon knowing that this size is determined by the arrivals and the service time distributions, the number of serving stations, the arrival and service discipline and the number of units in the queue.

In mono-channel models, attention is directed to determining an economically optimal value of \( \rho \). This value can be determined by knowing the unitary waiting costs of incoming ships for operation (\( c_1 \)) and the unitary cost of service station inactivity, both with service personnel and without (\( e_a, e_r \)). The optimal value of the service intensity factor is obtained by calculating the minimum cost for serving an unit [6,7].

For the optimal service station demand \( \rho_o \) the following expression is obtained:

\[
\rho_o = \frac{1}{1 + \frac{c_1}{e_a - e_r}} \quad (3)
\]

only valid when \( c_1 > e_a - e_r \), which corresponds to the situations encountered in practice.

If we consider the intervals between arrivals and service times corresponding to an exponential distribution it results that the optimal service station demand is even smaller as the ratio between the unitary cost of ships waiting time in the port and the unitary cost of remuneration of the servicing of the cranes \((e_a - e_r)\) is higher.

It is therefore natural that, in a rational exploitation, the time use of the ship’s operating equipment is much lower than time use of similar equipment used for loading or unloading wagons or trucks.

The maximum value of \( \rho_o \) is obtained for \( c_1 = 0 \) what is impossible in practice. Table 3 shows the \( \rho_o \) variation \( \rho_o = f(c_1/(e_a - e_r)) \).

To study the multi-channel mass-serving system, you need to go through the following steps:
the observation, based on a sample, of the empirical distributions of arrivals and ships service time, as well as the determination of the system solicitation degree;
- establishing the theoretical distribution of arrivals and of service times, corresponding to the observed distributions;
- determination of system parameters $\rho$ and $\bar{t}_o$ the analytical study of the problem to determine the changes to be made to the system (variation of $s$) in order to increase profitability.

**Table 3.** The $\rho_o$ variation.

| $\frac{c_1}{e_o - e_r}$ | 1 | 1,5 | 2 | 2,25 | 2,5 | 3 | 3,5 | 4 | 4,5 | 5 | 5,5 | 6 |
|--------------------------|---|-----|---|-------|------|---|------|---|------|---|------|---|
| $\rho_o$                 | 0,5 | 0,45 | 0,41 | 0,4 | 0,38 | 0,36 | 0,34 | 0,33 | 0,32 | 0,31 | 0,29 | 0,28 |

The variation coefficient $\nu$ (ratio between the dispersion and the average) provides a useful indication of the theoretical distribution that could approximate the observable empirical distribution of the arrival and service of ships in the port.

Table 4 presents the theoretical distributions with which the empirical distributions can be approximated, depending on the value of the variation coefficient.

**Table 4.** Theoretical distributions of random variables depending on $\nu$ [5].

| Variation coefficient | $\nu = 0$ | $0 < \nu < 0,33$ | $0 < \nu < 0,71$ | $0,71 < \nu < 1$ | $\nu \geq 1$ | $\nu > 1$ |
|-----------------------|-----------|------------------|------------------|-----------------|-------------|-----------|
| **Name of distributions** | Uniform (constant) | Normal | Erlang with different intensities $\lambda_1$ and $\lambda_2$ | Exponential | Hyper-exponential |

In conclusion, obtaining a rigorous minimum value of the objective function is a difficult issue because waiting time (ships waiting time and installations waiting time) is a parameter depending on many elements, some of them exogenous to the system.

**3. Case study**

For the model development the arrivals of ships in the port were first studied (for a period of 30 days). The situation is presented in Table 5.

**Table 5.** Ships arriving in port.

| Day | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|-----|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|
| **Number of ships arrived** | 5 | 4 | 4 | 3 | 6 | 1 | 3 | 2 | 2 | 3 | 0 | 6 | 4 | 3 | 1 |

| Day | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 |
|-----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| **Number of ships arrived** | 6 | 4 | 3 | 2 | 6 | 0 | 5 | 4 | 3 | 7 | 2 | 5 | 4 | 2 | 1 |

The number of ships arrived per day varies from 0 to 7. The concordance between the empirical repartition and the theoretical one considered is verified ($(M/M/s(\infty/FIFO) – Poisson distribution for arrivals and Exponential distribution for service time, with $s$ number of parallel servers/serving stations, $\infty$ places in the system and FIFO discipline queueing system).
Average and dispersion for the empirical random variable is \((m_n\text{ and } \sigma^2)\).

\[
m_n = \frac{1}{N} \sum_{n} n f(n) = 3.37
\]

(4)

\[
\sigma^2 = \frac{1}{N} \sum_{n} (n - m_n)^2 f(n) = 3.37
\]

(5)

In order to check the concordance between the empirical and the theoretical random variable, the \(\chi^2\) test is used. If \(\chi^2_{\text{calculat}} < \chi^2_{\text{tabulat}}\), then the conclusion that a good concordance exists between the two random variables can be drawn:

\[
\chi^2_{\text{calculat}} = \sum_{n} \left[ f(n) - NP_n \right]^2 \frac{NP_n}{NP_n} = 3.056
\]

(6)

\[
P_n = \frac{(m_n)^n}{n!} e^{-m_n}
\]

(7)

As we can see in the distribution table of \(\chi^2\) its value is in the confidence interval corresponding to \(P = 0.05\), \(\chi^2 = 12.59\) and it is higher than \(\chi^2\) calculat. It can be concluded that the observed frequency regarding ships arrivals in port corresponds to a Poisson distribution.

Similarly, based on observation, the ships service on berths was studied, determining that the service time also follows a Poisson repartition, checked with \(\chi^2\) test. The average service time for a ship \(\bar{t}_{sv}\), determined by statistical study, is 18 hours, and so, the average number of service in the time unit (24 hours a day) is; \(\mu = 1.34\) and \(\lambda = 3.37\).

So, \(\rho = \lambda / \mu = 2.52 > 1\). For one berth the queue increases to infinite and the system does not work in stationary regime. For the system to enter the stationary mode the service intensity factor of the system must be subunitary, \(\rho < 1\). This happens for a number of berths \(s\) equal to 3.

Verifying that the number of berths is appropriate will be achieved by calculating the main elements of the model for \(s = 3, 4, 5, 6, 7\) and 8.

\[
\hat{t}_{sv} = \frac{\rho^s}{s \cdot s! \mu (1 - \rho / s)^2} \cdot P(0)
\]

(8)

\[
P(0) = \frac{1}{s! \left(1 - \frac{\rho}{s}\right)} \sum_{k=0}^{s} \frac{\rho^k}{k!}
\]

(9)

The inactivity time for service stations \((D_{i})\) and medium waiting time of the ships for service \((D_{sv})\) are:

\[
D_{i} = s \cdot 24 - \lambda \bar{t}_{sv} \quad \text{and} \quad D_{sv} = \lambda \hat{t}_{sv}
\]

(10)

The waisting time of the ships waiting for service and berths inactivity cost \((c)\) is:

\[
C = c_1 D_{sv} + c_2 D_{i}
\]

(11)
The calculated values of the system parameters and the associated economic function are shown in table 6.

Form table 6 it is noticed that the minimum inactivity cost and ships waiting time cost of the is obtained for 5 berths, which is equivalent to a service intensity factor $\rho \approx 0.5$. For many port administrations it is unacceptable. So other organizational solutions have to be found.

### Table 6. The berth inactivity cost and ships waiting time cost.

| $s$ | $P (0)$ [zile] | $\bar{t}_a$ [h/zi] | $D_i$ [h/zi] | $D_e$ [h/zi] | Inactivity costs and waiting time costs |
|-----|----------------|---------------------|---------------|---------------|----------------------------------------|
|     |                |                     |               |               | $c_1 = 400$                             |
|     |                |                     |               |               | $c_1 = 500$                             |
|     |                |                     |               |               | $c_1 = 600$                             |
| 3   | 0.0428         | 1.1092              | 11.34         | 89.69         | 37010                                  |
|     |                |                     |               |               | 45979.00                               |
|     |                |                     |               |               | 54948.00                               |
| 4   | 0.0721         | 0.1652              | 35.34         | 13.34         | 8870                                   |
|     |                |                     |               |               | 10204.00                               |
|     |                |                     |               |               | 11538.00                               |
| 5   | 0.0784         | 0.0403              | 59.34         | 3.25          | 7234                                   |
|     |                |                     |               |               | 7559.00                                |
|     |                |                     |               |               | 7884.00                                |
| 6   | 0.0799         | 0.0105              | 83.34         | 0.8492        | 8673                                   |
|     |                |                     |               |               | 8758.60                                |
|     |                |                     |               |               | 8843.52                                |
| 7   | 0.0803         | 0.0026              | 107.34        | 0.2159        | 10820                                  |
|     |                |                     |               |               | 10841.95                               |
|     |                |                     |               |               | 10863.54                               |
| 8   | 0.0812         | 0.0007              | 131.34        | 0.0527        | 13155                                  |
|     |                |                     |               |               | 13160.35                               |
|     |                |                     |               |               | 13165.62                               |

### 4. Conclusion

The development of port facilities can be achieved through models based on minimizing waiting costs of both port installations and for ships arriving in port. Even when these elements are known, the practical application of mass-serving theory models can create problems in terms of complicated and difficult to handle mathematical expressions that can be achieved in modeling the system.

It is known that today many ships are equipped with their own loading / unloading facilities which makes it difficult to define the serving characteristics. When designing port equipment sizes, it is difficult to determine the number of service stations.

When the waiting costs are unknown, then the rational dimensioning of the port equipment can be achieved using models based on the levels harmonization, given that these models compare the parameters of the system.

The problem with these models is the choice of the upper limits of the parameters that are harmonized. These can be adopted by comparison with other similar ports in terms of size and activity, ports that are recognized as operating at maximum profitability.

The using of mass serving theory models leads to a rational dimensioning of port facilities with direct implications in reducing the ships and port installations costs of waiting times. Policies applied depend on the costs involved in the sizing process, which may vary from one area to another and even in time.

### Acknowledgement

This work has been funded by University Politehnica of Bucharest, through the “Excellence Research Grants” Program, UPB – GEX 2017. Identifier: UPB- GEX2017, Ctr. No. 65/25.09.2017 (GEX2017).

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