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Modelling Support for Maritime Terminals Planning and Operation

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ABSTRACT: The maritime terminal design process is a complex stepwise series of strategic decisions involving the engagement of a relevant amount of resources. In fact operating conditions near the maximum capacity cause congestion effects with negative consequences on regularity and quality service. Therefore, in order to maximise its effectiveness, a strong need of methodological support is required. With this aim the authors developed different methods and models capable of supporting some of these decisions: a regressive method for preliminary dimensioning of harbour terminals and a sea-side operation combinatorial model for traffic analysis and capacity estimation. They are able to be integrated in a chain of models taking into account dimensions and manoeuvrability of ships, terminal morphology, handling equipment, storage areas, etc., with the aim to support the planning process and operational management.

1 INTRODUCTION

The design process is a complex stepwise series of strategic decision involving the engagement of a relevant amount of resources.

Therefore, in order to maximise its effectiveness, a strong need of methodological support is required.

With this aim the research group of the authors developed different methods and models capable to support some of these decisions:

- regressive method for preliminary dimensioning of container terminals;
- sea-side operation combinatorial model;
- synthetic method capable of validating the estimates of the capacity combinatorial model.

It is possible to integrate the models in a chain taking into account, within a stepwise methodological approach, dimensions and manoeuvrability of the ships, positions of terminals, accessibility, handling equipment, storage areas, etc.

2 PRELIMINARY DIMENSIONING METHOD

The preliminary dimensioning method allows to select the parameters most suitable to describe terminals, to determine their dimensional and equipment characteristics and to verify their production, as well as to provide inputs, defined in terms of production or number of ships, for the combinatorial model capable of evaluating sea-side port capacity (Florio & Malavasi, 1995).

2.1 Definition of key parameters

Maritime container terminals are infrastructures provided with equipment for the transfer of containers from ship to docks and back.

They are integrated into logistic structures of most commercial ports.

In any terminal fundamental and complementary activities are identifiable:

- container loading and unloading; 1
- sea-side and land-side (railway and road) stock-2 ing operations;
- 3 traffic management and control;
- 4 container clearance for international traffic;
- 5 storage and reorganisation of freight into containers

Structures and performances of terminals, deduced from a first analysis, may be synthetically represented in three main clusters of parameters (Noli & al. 1984) respectively representing dimensions, equipment and production:

- A. Dimensional parameters:
 - 1) Ouay length.
 - 2) Total stacking area,
 - 3) Covered stacking area,
 - 4) Uncovered stacking area;

B. Equipment parameters:

- 5) Number of gantry cranes,
- 6) Number of other cranes,
- 7) Number of storage cranes,
- 8) Number of various loaders;

C. Production parameters:

- 9) Number of handled containers.
- 10) Number of handled TEU,
- 11) Number of handled container tonnage.

For these parameters an extensive investigation on port terminals for data acquisition has been carried out.

2.2 Definition of the area of analysis

The ports analysed are located in Northern Europe (Atlantic Ocean, Baltic Sea and North Sea) and in Mediterranean area (Ricci & al. 2008b).

In this area 73 ports, dealing with relevant container traffic, have been identified.

For 93 container terminals located in 49 of these ports useful data have been collected and elaborated.

In Table 1 the amount of observations available for the analysed parameter is shown.

Table 1. Observations available for analysed parameters

Parameters	Observation		
	N°		
Quay length	93		
Total stocking area	91		
Covered stocking area	91		
Uncovered stocking area	29		
Gantry cranes	85		
Other cranes	37		
Storage cranes	59		
Various loaders	57		
Containers	19		
TEU	72		
Tonnage	30		

2.3 Application of methodology

In the proposed regressive approach an analysis has been performed on the relationships between parameters:

- 1. belonging of the same cluster (as defined above);
- 2. belonging of different cluster.

The amounts of data useful for the correlations are summarised in a matrix (Fig. 1).

Figure 1 Available observations by couples of parameters

The collected and homogenised data has been correlated by means of a linear regression obtaining the correlation coefficients R.

All the values have been filtered with different *R* threshold values (0.7 and 0.8).

In Figures 2 and 3 the values of coefficient R of the regression lines are presented in matrices.



Figure 2: Correlations between couples of parameter with 0.7 as threshold of relevance

1	QUAY LENGTH	1										
2	TOTAL STOCKING AREA	0,892	2									
3	COVERED STOCKING AREA	0,518	0,963	3								
4	UNCOVERED STOCKING AREA	0,621	0,971	0,921	4							
5	GANTRY CRANES	0,745	0,925	0,228	0,032	5						
6	OTHER CRANES	0,217	0,410	0,118	0,827	0,000	6					
7	STORAGE CRANES	0,769	0,805	0,905	0,100	0,809	0,232	7				
8	VARIOUS LOADERS	0,551	0,601	0,551	0,330	0,542	0,212	0,764	8			
9	CONTAINER (NUMBER)	0,349	0,925	0,966	0,825	0,935	0,815	0,844	0,777	9		
10	CONTAINER [TEU]	0,706	0,910	0,207	0,134	0,770	0,224	0,823	0,559	0,999	10	
11	CONTAINER [TONNELAGE]	0,513	0,945	0,983	0,173	0,947	0,462	0,936	0,738	0,999	0,996	- 11

Figure 3: Correlations between couples of parameter with 0.8 as threshold of relevance

On this basis it is possible to represent the relationships between parameters corresponding to shortest paths on graphs of Figure 4.



Figure 4: Graphs of the relevant correlations with $R \ge 0.7$ and $R \ge 0.8$

2.4 Direct and indirect correlations between parameters

The main feature of the proposed methodology is the possibility to calculate on a probabilistic basis the main design parameters (dimensions, equipment, etc.) by means of the correlations with flow parameters and to calculate flow and equipment parameters by means of the correlations with dimensional parameters.

For this purpose it is necessary to determine also the direct relationships and the indirect ones requiring intermediate parameters to link inputs and outputs. For the selection of shortest paths (highest global correlation) the Dijkstra algorithm has been applied.

Starting from the inputs corresponding to production parameters (containers, TEU and tonnage) or to dimensional ones it is possible to define the tree of shortest paths with the parameters linked directly and indirectly.

Different scenarios have been obtained by combination of threshold value (0.7 and 0.8) of correlation parameters with possible input parameters (Figures 5-11).



Figure 5: Shortest paths starting from the number of containers (threshold R>0,7 and R>0,8)



Figure 6: Shortest paths starting from TEU (threshold R>0,7 and R>0,8)



Figure 7: Shortest paths starting from containers tonnage (threshold R>0,7 and R>0,8)



Figure 8: Shortest paths starting from quay length (threshold R>0,7 and R>0,8)



Figure 9: Shortest paths starting from total stocking area (threshold R>0,7 and R>0,8)



Figure 10: Shortest paths starting from covered stocking area (threshold R>0,7 and R>0,8)



Figure 11: Shortest paths starting from uncovered stocking area (threshold R>0,7 and R>0,8)

2.5 *Case study*

The regressive method (Ricci & al. 2008b) has been applied to the pilot case represented by the Darsena Toscana container terminal in the port of Livorno (Table 2).

Table 2. Leghorn Darsena Toscana container terminal (2007)

Parameters		Data
Quay length	[m]	1.430
Total stocking area	$[m^2]$	412.000
Containers	[n]	323.708
TEU	[n]	500.000
Tonnage	[t]	6.677.350

On the basis of arrivals and departures of container ship to/from Calata Massa, relating to Terminal Darsena Toscana quay, it has been possible to determine the capacity margin in 2007 expressed in number of ships per day that are can be moored alongside the above-mentioned quay.

The comparison between values of dimension, equipment and production parameters estimated by the model and real values are summarised in Figures 12-15.



Figure 12 Comparison between estimated and real values of quay length and total storage area



Figure 13 Comparison between estimated and real values of gantry cranes



Figure 14 Comparison between estimated and real values of container Lo-Lo and tonnage Lo-Lo



Figure 15 Comparison between estimated and real values of TEU and gantry cranes

2.6 Remarks

The values of parameters estimated by means of R threshold (0,7 or 0,8) are comparable, therefore their choice may be considered not relevant.

The most reliable results are obtained by means of production parameters as input data, in particular the number of handled container for the determination of quay length, total stocking area and gantry cranes. Indeed the other parameters are strongly influenced by local organizational issues and for this reason less suitable to be dealt with in a general approach.

3 SEA SIDE OPERATION COMBINATORIAL MODEL

Sea-side port operation, characterised by the overlap of the traffic of many different ships traffic often causes congestion effects with negative consequences on transport service regularity.

In this framework models (Potthoff, 1979) capable of simulating the operation of sea-side port terminals, of evaluating their capacity and of calculating the occupation time of the terminal by ships and its utilisation degree both in regular and perturbed (because of external causes or the congestion itself) conditions and of relating it with the quality of the transport services are very effective and allow to reach specific objectives:

- operational time saving;
- rational land-use (better planning of sea front);
- prevention of losses due to possible accidents and incidents;
- sensitivity of performances to variations in port terminal lay-out.

3.1 Specific research objectives

From the above arise considerations the specific objectives of the present researches that is build up models capable of:

- 1) simulating the terminal operation;
- 2) evaluating the terminal carrying capacity;
- 3) relating the utilisation degree of the terminal with its service quality.

The application of combinatorial synthetic models to sea terminals (Ricci & al. 2007) requires the introduction of the factors characterising the ships (dimensions and maneuvering with related kinematic and geometric constraints regulated movements), the terminal itself (different type of basin morphology or layout as shown on Figure 16).

In order to determine time interdiction between ship movements entering/exiting maneuvering movements are divided in 5 phases:

- 1 Approach to mouth,
- 2 Access to the channel,
- 3 Rotational movement,
- 4 Approach to the quay,
- 5 Anchorage.



Figure 16 Typical port layouts subjected to analysis

The carrying capacity of the terminal corresponds to the maximum number of movements allowed during the reference time and it depends mainly upon the following factors:

- time distribution of entering and exiting movements to/from the port and related assignment to the docks;
- terminal topology defined by the location of docks and the mouths.

The model approach is based on a constant probability for the arrivals i.e. a fixed number of movements for each route in the reference time.

This condition well represents both:

- high frequency of arrivals in peak periods;
- usual data availability in the planning phase, without detailed information on ship scheduling.

This condition is formally defined by an array P, with dimensions corresponding to the number of the

routes in the terminal and single elements p_i defining the number of movements on each route in the reference time T.

The analysis of the terminal morphology allows to define the whole set of routes and their reciprocal compatibility/incompatibility represented in a square matrix (compatibility matrix) $C = P \ge P$, with each element c_{ij} representing the condition of compatibility/incompatibility between routes *i* and *j*.

The possible relationships are:

- incompatibility between two routes with:
 - a. common final/initial sections,
 - b. common middle sections,
 - c. same path but opposite direction;
- compatibility between two routes without common sections, allowed to be run contemporarily.

The proposed approach allows to calculate the mean number of possible simultaneous movements n by taking into account the compatibility of the routes and their frequency of utilisation:

$$n = \frac{N^2}{\sum_{ij} m_{ij}} \tag{1}$$

where:

- $m_{ij} = p_i \ge p_j$ if *i* and *j* are incompatible;
- $m_{ij} = 0$ if *i* and *j* are compatible.
- -N is the total number of movements during reference time *T*.

In a similar way the mean terminal utilisation time can be defined as:

$$t = \frac{\sum_{ij} m_{ij} \cdot t_{ij}}{\sum_{ij} m_{ij}}$$
(2)

where t_{ij} is the time during which the route *j* may not be run because a ship is moving on the route *i* (interdiction time).

The total occupation time can be calculated as:

$$B = \frac{N}{n} \times t \tag{3}$$

In order to take into account the waiting situations due to simultaneous arrivals on incompatible routes it is possible to calculate the delay imposed by the p_i movements on the p_j movements because of the interdiction time t_{ij} :

$$r_{ij} = \frac{p_i p_j t_{ij}^2}{2T} \tag{4}$$

these parameters allow the comparison between the total utilisation time of the terminal, including the delays, and the reference time. The utilisation degree can be calculated with reference only to the situation of regular running on routes, as:

$$U = \frac{B}{T} \tag{5}$$

Or reference to the total time, including the delays, as:

$$V = \frac{B+R}{T} \tag{6}$$

where:

$$R = \frac{\sum_{ij} r_{ij}}{n} \tag{7}$$

3.2 Applications and remarks

The model has been applied to five Italian ports (Ancona, Bari, Brindisi, Gioia Tauro and Livorno) characterised by three different morphologies (circular, channel and tree layout).

The results of the model application are summarised in Table 3.

Table 3 Capacity limit for analysed port [movements/day]

Port	Ancona	Bari	Brindisi	Gioia T.	Livorno
Observed movement	33	23	27	18	41
Maximum capacity	61	70	49	40	53

The port with a circular morphology normally shows a higher capacity limit than the other ones, due to shorter routes and shorter interdiction times between movements.

The channel ports show a lower capacity than ports with tree layout, due to a lower number of basins that are able to let an early release of common sections between entering/exiting route.

For these ports largest capacity are related to number of quay basins and consequently to their rotation basins as well as to the assignment of docks to ships characterised by less manoeuvrability (e.g. liquid/solid bulk and container ships) in specific part of ports.

4 COMPARATIVE MODELS

In order to validate on a comparative basis the previous model and its results, two alternative models for the evaluation of port capacity have been identified; they are based on:

- Channel capacity,
- Minimum spacing.

These models are characterised by a fewer input data and able to analyse the particular basin channel morphology or a specified part of a port terminal referable to this specific characteristic (Ricci & al. 2008a).

4.1 Models based on channel capacity

The port system is schematically structured into three parts (Fig. 17):

- the waiting basin, where ships arrive and wait to enter the channel;
- the entering area, where only the ship approaching the channel is admitted;
- the channel itself.



Figure 17 Port schematisation for channel capacity method

As soon as the ship in the entering area approach the channel, the following one enters this area at the minimum separation distance.

The following hypotheses are considered for the calculations:

- ship arrivals according to the Poisson distribution;
- infinite capacity of the waiting basin;
- fixed speed for each ship in the channel;
- deterministic separation distance between ships;
- fixed fleet composition;
- permanent communication between ship and traffic controller;
- ship characteristics known in advance by traffic controller;
- irrelevant wind effects;
- permanent availability of pilots and tugboats;
- 24 hours/day operation;
- balanced entering and exiting flows.

By adopting the Permanent International Association of Navigation Congress (PIANC) expression for the stopping distance is:

$$D = 4L \times \left(\frac{V}{2.5}\right)^{0.75} + L \tag{8}$$

This distance is increased to take into account adverse weather conditions (+50%), approximation in speed measurement (+40%) and additional safety rate (+20%):

$$D = \frac{L}{60} \times \left(0.235 \times V^{0.75} + 1.8\right)$$
(9)

The minimum separation time S_{IJ} between a couple of ships *I* and *J* further depends upon the speed strategy adopted in the channel (single speed or multi-speed) and is calculated at the generic ship *I* dock, whose distance from the channel entering is LC_I :

$$S_{IJ} = \frac{(D_J + L_I)}{V_I} + (LC_I - D_J) \times MAX \left[\left(\frac{I}{V_I} - \frac{I}{V_J} \right); 0 \right] (10)$$

The probability P_{IJ} that the generic arriving ship has a separation time S_{IJ} from the following one is the product $P_I \ge P_J$ of the corresponding probability of arrival of ships I and J.

Therefore the mean service time is:

$$E(S) = \sum_{I} \sum_{J} S_{IJ} P_{IJ} = \sum_{I} \sum_{J} S_{IJ} P_{I} P_{J}$$
(11)

and the maximum arrival rate, corresponding to the capacity of the system, according to this method, may be calculated as:

$$\lambda_{MAX} = \mu = \frac{l}{E(S)} \tag{12}$$

The whole methodology is represented in Figure 18 flowchart.



Figure 18 Channel capacity methodology

4.2 Models based on minimum spacing

The capacity corresponds to the maximum amount of movements possible within defined time interval under continuous demand service, corresponding to saturation conditions.

The input required by this model is limited to arrival delays, which can be easily calculated or estimated for any port.

Moreover the definition of operational rules, followed by the ships under saturation conditions, is required taking into account that port basin and approaching zones are considered as a whole.

Arrivals always have priority on departures, moreover an exiting ship may be authorised to move only the minimum spacing from the previous movements is reached.

Two possibilities exist (Fig. 19):

- if the second ship is faster than the first one the minimum spacing d will be located at the port mouth;
- if the first ship is faster than the second one the minimum spacing d will be located at the pilot point (where the ship is manoeuvred by personal of The Port Authority).



Figure 19 Minimum spacing location

The perfect coordination of arrivals is obviously impossible, therefore the spacing is normally higher:

$$D = d + B \tag{13}$$

where *B* is a buffer depending upon the traffic regularity level, which is normally possible to define according to a standard normal distribution.

Moreover a departure may be allowed only if the crossing with the first arriving ship is located at a spacing D.

Therefore, if a departure (ship 1) is followed by an arrival (ship 2) the time interval between two departures (ships 1 and 3) is defined as:

$$\Delta t_{13} = t_{u1} + \frac{D}{V_1} + \frac{D}{V_2} t_u + t_{e2}$$
(14)

where:

- V_1 and V_2 are the speeds of the ships outside the port mouth;
- *t_{u1}* and *t_{e2}* are the mean exiting and entering times for the ships, calculated according to traffic mix and dock location;

The whole methodology is represented in flowchart Figure. 20.

4.3 Applications of the two models and remarks

The capacity values have been estimated:

- for the port of Gioia Tauro on the basis of the overall number of entering/exiting daily movements (19);
- For the port of Livorno on the basis of the entering/exiting number daily movements in the section before Darsena n°1, Canale Industriale and Calata Gondar basins that is possible to assimilate to a channel.



Figure 20 Minimum spacing methodology

The key results of the comparison between the model based on the mean number of movements and the alternative models are reported in Table 4.

Table 4 Comparison of model results [movements/day]

Model	Gioia Tauro	Livorno
Channel	35	64
capacity Minimum Spacing	29	29
Mean number of movements	40	53

For the channel port of Gioia Tauro the results are similar.

In the case study of the port of Livorno (tree layout) relevant differences exist, particularly for the minimum spacing model, which seem unsuitable for the application to tree lay-out ports.

The original model based on the calculation of mean number of movements seems well reproducing the average capacity volumes for the analysed typical port lay-outs.

5 CONCLUSIONS

A stepwise approach is presented allowing:

- to dimension a harbour terminal (container terminal) in terms of optimal storage capacity, geometrical and operational characteristics, starting from freight handled in a reference time interval;
- to estimate terminal capacity expressed by the number of ships able to use the port equipments in addition to regular and daily traffic inside the port in defined service regularity conditions (under the influence of considered additional movements);
- to identify a qualitative correspondence between analysed different port lay-outs and respective manoeuvring capacity.

REFERENCES

- Florio L., Malavasi G., 1995. Introduzione all'analisi strutturale degli impianti portuali di trasbordo container, Ingegneria Ferroviaria, August, 454.
- Malavasi G., Marinacci C., Ricci S., 2007. *Capacità portuale lato mare: un modello di valutazione sintetica* – Binari sul mare. Scenari di integrazione del trasporto merci, Officina edizioni, Roma.
- Malavasi G., Marinacci C., Ricci S., 2008. *Performances and application fields of sea side port capacity models* AATT 2008, Athens.
- Malavasi G., Ricci S., 2002. Generalized model for the performance evaluation of different railway freight terminals. 9th

International Symposium, Railways on the Edge of the 3rd Millennium, Zilina.

- Marinacci C., Quattrini A., Ricci S., 2008. Integrated design process of maritime terminals assisted by simulation models – MMS 2008 The International Workshop on Harbour, Maritime & Multimodal Logistics Modelling and Simulation, Briatico.
- Noli A. and others, 1984. Calate portuali e terminali marittimi. Criteri generali di pianificazione e costruzione, Roma, ESA.
- Park C.S., Noh Y.D., 1987. An interactive port capacity expansion simulation model – Engineering Costs and Production Economics, Volume 11, Issue 1 (109-124).
- Potthoff G., 1979. Verkehrsströmungslehre, Vol. 1-5 Transveb, Berlin.