INTEGRATED DESIGN PROCESS OF MARITIME TERMINALS ASSISTED BY SIMULATION MODELS

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ABSTRACT
The port design process plays a key role both in the planning of the infrastructures and in quality of provided transport services.
In fact operating conditions near the maximum capacity cause congestion effects with the concerned negative consequences on capacity and regularity.
In this framework, models capable to support the design process, in terms of infrastructural and equipment dimensioning, as well as to simulate the operation of the sea-side and land-side port terminals, to evaluate their capacity and to relate the terminal utilisation degree with the quality of the transport services are very effective.
The paper describes a chain of regressive, analytical and combinatorial models, which has been developed by taking into account, within a stepwise methodological approach, dimensions and handiness of the ships, positions of terminals, accessibility, handling equipment, storage areas.
The results of a pilot application to the Italian port of Livorno are presented.

Keywords: ports, design, model

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

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

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

- sea-side operation combinatorial model;
- regressive method for preliminary dimensioning of container terminals;
- container terminals operation stochastic model.

They are able to be integrated in a chain taking into account, within a stepwise methodological approach, dimensions and handiness of the ships, positions of terminals, accessibility, handling equipment, storage areas, etc.

2. SEA SIDE OPERATION COMBINATORIAL MODEL
The sea-side port operation, characterised by the overlap of many different ships traffic causes very often congestion effects with negative consequences on the transport services regularity.

In this framework models capable to simulate the operation of the sea-side port terminals, to evaluate their capacity and to relate the terminal utilisation degree with the quality of the transport services are very effective and allow to reach specific objectives:

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

Applications on other terminals (railway stations and airports) demonstrated the effectiveness of synthetic models capable to calculate the occupation time of the terminal by the vehicles and the utilisation degree on the basis of a generic operation plan, both on regular and perturbed (because of external causes or the congestion itself) conditions.

These effects are particularly relevant for the fast passengers ships: in fact the advantage to use this kind of ships, which are now strongly extending their market, may be reduced because of the typical congestion conditions during the port entering and exiting movements.

2.1. Specific research objectives
From the considerations above arise the specific objectives of the present research, which is aimed to build up models capable to:

a) simulate the terminal operation;
b) evaluate the terminal carrying capacity;
c) relate the utilisation degree of the terminal with its service quality.

The application of combinatorial synthetic models to the sea terminals requires the introduction of the factors characterising the terminal itself and the ship (dimensions and handiness with related cinematic and geometric constraints, regulated movements).

2.2. Methodology description

The model is based on the schematisation of ships routes from the port mouth to the docks, which may be partially or totally independent according to the basins morphology and to the safety rules adopted by the port authority.

They depend mainly on the handiness and the dimensions of the ships, which strongly effect their capability to avoid the risk of collisions.

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

The model approach is based on a constant probability for the arrivals: the demand is known in terms of number of movements for each route in the reference time.

This condition is well representing both:

- high frequency of the arrivals in the peak periods;
- usual data availability in the planning phase, when you necessarily don't possess detailed information on the future ships 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 the routes and their reciprocal compatibility/incompatibility.

The compatibility relationships are represented in a square matrix (compatibility matrix) $C = P \times P$, with each element c_{ij} representing the condition of compatibility/incompatibility between the routes i and j.

The possible relationships are:

- incompatibility between two routes with:
  d) common final/initial sections,
  e) common middle sections,
  f) same path but opposite versus;
- compatibility between two routes without common sections, allowed to be run contemporarily.

The proposed approach allows to calculate the mean number of possible contemporary 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:

- $m_{ij} = p_i \times p_j$ if i and j are incompatible;
- $m_{ij} = 0$ if i and j are compatible.

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

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

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) and N is the total number of movements during T.

The total occupation time can be calculated as:

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

In order to take into account the waiting situations due to contemporary 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 regular running on the routes as:

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

or to the total time, including the delays, as:

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

where is:

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

2.3. Model application

The methodology has been validated by means of pilot applications to the port of Livorno (figure 1), located on the middle of the Italian west coast.

The port is shaped as a basin where the docks and the evolution areas are protected on the sea-side by a jetty mainly parallel to the coast line.

This morphology influences the entering and exiting movements because it does not allow, in many cases, more than a single movement.

Figure 1: Lay out of port of Livorno

The long distance from the port mouth to the most far dock (up to 1800 m) causes long interdiction times. The elements characterising the traffic within the basin are:

a) limited speed allowed within the port (6 knots ≈ 10 km/h);
b) long manoeuvre time because of both the dimensions of the ships (up to 250 m long) and the required assistance (tugboats, mooring men, pilots, etc.);
c) concentration of the manoeuvres in restricted evolution areas, which limits the use of the main channel for other movements and may require more than a tugboat;
d) rare movements compatibility, due to the several sections common to various routes (particularly near the channel mouth).

Therefore, though the flows are quite low, the interdiction times are high and the compatible movements are rare.

Further constraints are related with some organisational aspects, particularly the limited amount of some key resources:

- the pilots (its presence is mandatory during the movement within the port);
- the tugboats (the most part of the movements requires at least a tugboat).

The terminals include 21 docks distributed in 6 mooring basins (figure 2) equipped for loading/unloading of freight and passengers, that means 42 routes between them and the port mouth.

Figure 2: Mooring basins of the port of Livorno

The assignment of the ships to the docks depends on the ships characteristics, the presence of loading/unloading equipment and the accessibility from/to the land transport systems (land-side terminal).

Nevertheless, for the carrying capacity analysis, the routes from/to the adjacent docks can be grouped by taking into account that the manoeuvres from/to them must be run once.

In the meantime the common considered interdiction time takes obviously into account the whole route to the dock.

The routes couples comparison allows to build up the compatibility matrix.

In the present study the following classes of ships are considered:

a) fast ships (HSC) capable to run at 75 km/h and to manoeuvre without the help of tugboats;
b) modern Ro-Ro and Ro-Pax ships also manoeuvring without the help of the tugboats;
c) traditional ferries, requiring the tugboats for manoeuvring;
d) freight ships, which can require up to 3 tugboats and, if transporting fuels or other dangerous freight, need particular care because of the safety rules;
e) cruise ships.

The entering movement is composed by various phases, with run time depending on the characteristics of the ships, the distance to be run for reaching the assigned dock, the maximum allowed speed and the time required by the dock approach.

The following phases can be usually identified:

- approach to the port mouth, with speed decreasing from the cruise speed to the maximum speed allowed for the entering movements (about 6 knots ≈ 10 km/h): the ship leaves its course for running the entering route;

- running in the channel from the port mouth to the evolution basin, whose extension is depending on the assigned dock;
- evolution, consisting of the ship rotation operated with the help of the tugboats or by means of the transversal propulsion systems on board;
- approach to the dock, to be operated with the help of the tugboats or by means of the warps or the ship propulsion systems themselves;
- ship locking and pre-arrangement of the freight and/or passengers loading/unloading operation.

In figure 3 the mean values of the manoeuvre times calculated for different basin, by taking into account the docks usually assigned, are listed.

Basin / Manoeuvre	A	B	C	D	E	F
Port mouth approach	7	7	7	7	7	7
Channel running	7	9	13	18	21	26
Evolution	5	5	5	5	5	5
Dock approach	6	6	6	6	6	6
Locking	3	6	6	6	6	6
TOTAL	28	33	36	42	45	50

Figure 3: Main manoeuvre times for each basin [min]

The exiting movements are symmetric in the most cases.

Insofar the interdiction time depend on the safety criteria adopted by the port authorities for avoiding the possible conflicts, which are generally based on the evaluation of the related risks.

Obviously rigid safety criteria impose rigid routes release criteria, which cause long interdiction times; on the contrary flexible criteria, allowing the progressive release of the sections and the contemporary ship movements at a given distance, reduce the interdiction times themselves with positive effects on the carrying capacity of the port terminal.

The evaluation of the utilisation degree was carried out on the basis of the real traffic flows scheduled for the peak day of year 2007 with 63 movements/day distributed during 23 hours (figure 4).

A Bacino Firenze Bacino Cappellini		B Bacino S. Stefano		C Darsena Pisa		D Darsena Toscana		E Darsena n°1		F Canale Industriale	
Molo Elba 66 n	5	Alto Fondale 45	2	Silos tirreno	2	Calata Lucca 15a	5	Adis Abeba 20	3	Darsena ugione 36 a	1
Calata Sgarallino 62	9	Alto Fondale 46	2	Doc	2	Calata Massa 14 b	8	Assab	2	Sintemar 24 c	3
Calata punto Franco	4					Tripoli 16	4	Gondar 19	2	Novaol 27	1
Molo capitaneria 64 n	1									Costieri D'alesio 29 n	3
Calata Carrara 55	4									Grandi molini italiani	1
										Leonardo Da vinci	2

Figure 4: Distribution by basin of arrivals/departures

The corresponding flows distribution on the routes is represented in figure 5.

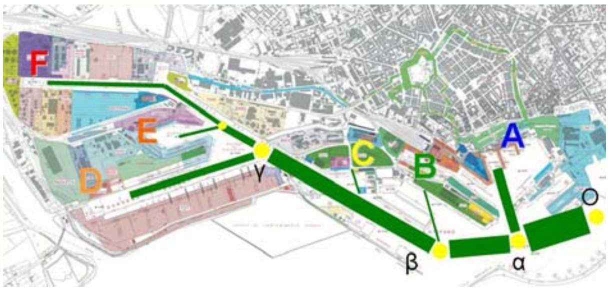

Figure 5: Flows distribution on the routes

On this basis have been calculated the utilisation degree summarised in figure 6.

The mean values of the utilisation degree under perturbed conditions (V) for the whole daily operation period is about 1,65, while the mean value of it under regular conditions (U) is about 0.8.

Further elements on the carrying capacity can be evaluated by analysing the effects on the utilisation degree of traffic variation, which, on the basis of a maximum reference level of V=0,65, shows a total carrying capacity value under regular conditions of 48 movements / 23 hours (-15 Movements = -24% in comparison with the present situation), which highlights a substantial congestion condition in the present operation.

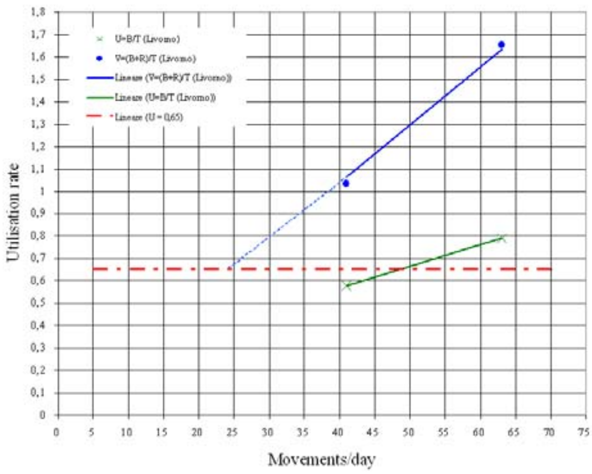

Figure 6: Utilisation degree of Livorno port

Further differences (up to 20%) may be related to different distributions of ships classes and routes utilisation.

3. REGRESSIVE METHOD FOR PRELIMENTARY DIMENSIONING OF CONTAINER TERMINALS

The maritime container terminals are infrastructures provided with considerable equipments able to overtake the transfer of containers from ship to docks and back.

They are integrated into logistic structures of the most part of commercial ports.

In any terminal fundamental and complementary activities are identifiable:

1. containers loaded and unloading;
2. sea-side and land-side (railway and road) stocking area;
3. traffic management and control;
4. container clearance for the international traffic;
5. storage and reorganization of freight into containers.

Structures and performances of terminals, deduced from a first analysis, may be synthetically represented in three main clusters of parameters respectively representing dimensions, equipment and production:

A. Dimensional parameters:
   - Quay length (1),
   - Total stacking area (2),
   - Covered stacking area (3),
   - Uncovered stacking area (4);
B. Equipment parameters:
   - Gantry cranes (5),
   - Other cranes (6),
   - Storage cranes (7),
   - Various loaders (8);
C. Production parameters:
   - Number of handled containers (9),
   - Number of handled TEU (10),
   - Handled container tonnage (11).

For these parameters an extended investigation on operated port terminals for data acquisition and homogenisation has been carried out..

3.1. Definition of the analysis area

The main analysed ports are located in North Europe and in Mediterranean area.

In this area have been identified 73 ports interested by relevant container traffic.

For 93 containers 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

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

Lower amount of observations are available for information more difficult to be obtained.

3.2. Methodology application

In the proposed regressive approach have been analysed relationships between parameters:

1. of the same cluster;
2. of different classes.

The amount of useful data for the correlations are summarised in a matrix (figure 7).

N	1	2	3	4	5	6	7	8	9	10	11
1											
2	88										
3	77	91									
4	23	29	28								
5	72	79	79	20							
6	29	35	28	10	24						
7	49	74	46	10	48	22					
8	47	51	39	10	45	23	40				
9	14	19	19	5	18	8	12	12			
10	55	69	63	17	61	25	46	32	17		
11	20	28	27	8	27	16	18	20	12	29	

Figure 7: Available observations by couple of parameters

The collected and homogenised data has been correlated by means of a simple linear regressive method obtaining the correlation coefficients *R*.

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

In figures 8 and 9 the values of coefficient *R* of the regression lines are presented in matrices.

On these basis it is possible to look for the most direct relationships between parameters corresponding to shortest paths on a graph (figures 10 and 11).

		1	2	3	4	5	6	7	8	9	10	11
1	Quay length											
2	Total stacking area	0,892										
3	Covered stacking area	0,518	0,963									
4	Uncovered stacking area	0,621	0,971	0,921								
5	Gantry crane	0,745	0,925	0,228	0,032							
6	Other crane	0,217	0,410	0,118	0,827	0,000						
7	Storage crane	0,769	0,805	0,905	0,100	0,869	0,232					
8	Various loader	0,551	0,601	0,551	0,330	0,542	0,212	0,764				
9	Containers Lo-Lo	0,346	0,925	0,966	0,825	0,935	0,815	0,844	0,777			
10	TEU	0,706	0,910	0,207	0,134	0,770	0,224	0,823	0,559	0,999		
11	Tonnage Lo-Lo	0,513	0,945	0,983	0,173	0,947	0,462	0,936	0,738	0,999	0,996	

Figure 8: Correlations between couples of parameter with 0.7 as threshold of relevance

		1	2	3	4	5	6	7	8	9	10	11
1	Quay length											
2	Total stacking area	0,892										
3	Covered stacking area	0,518	0,963									
4	Uncovered stacking area	0,621	0,971	0,921								
5	Gantry crane	0,745	0,925	0,228	0,032							
6	Other crane	0,217	0,410	0,118	0,827	0,000						
7	Storage crane	0,769	0,805	0,905	0,100	0,869	0,232					
8	Various loader	0,551	0,601	0,551	0,330	0,542	0,212	0,764				
9	Containers Lo-Lo	0,346	0,925	0,966	0,825	0,935	0,815	0,844	0,777			
10	TEU	0,706	0,910	0,207	0,134	0,770	0,224	0,823	0,559	0,999		
11	Tonnage Lo-Lo	0,513	0,945	0,983	0,173	0,947	0,462	0,936	0,738	0,999	0,996	

Figure 9: Correlations between couples of parameter with 0.8 as threshold of relevance

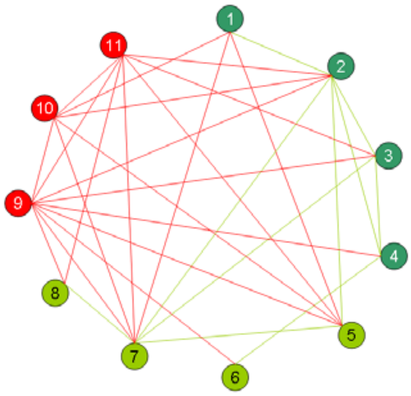

Figure 10: graph of the relevant correlations with R > 0.7

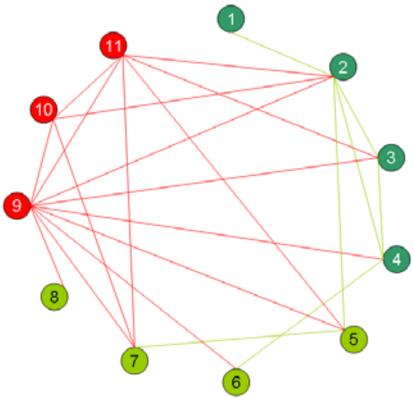

Figure 11: graph of the relevant correlations with R > 0.8

3.3. Indirect correlations between parameters

The main performance of the proposed methodology is to calculate on probabilistic basis the main design parameters (dimensions, equipment, etc.) by means of the generalisation of relieved correlations linked them to flow parameters (TEU, tonnage, etc.).

For this purpose it is necessary to determine also the indirect relationships requiring intermediate parameters able to establish between inputs and outputs. Normally different routes exist in the correlations graph. For the selection of shortest paths (highest global correlation) has been applied the Dijkstra algorithm.

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

Six different scenarios have been obtained by combination of threshold value (0.7 and 0.8) of correlation parameters with possible input parameters (figures 12 to 16).

3.4. Methodology application

The regressive method has been applied to the pilot case represented by the terminal container of the port of Livorno Darsena Toscana.

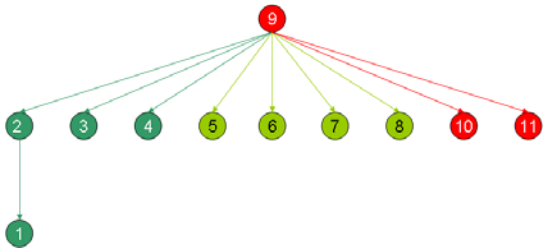

Figure 12: Shortest paths starting from the number of containers (threshold R=0.7 and R=0.8)

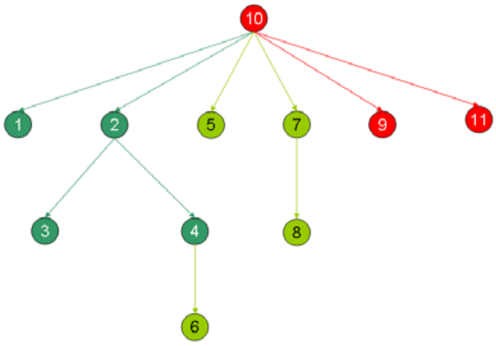

Figure 13: Shortest path starting from TEU (threshold R=0.7)

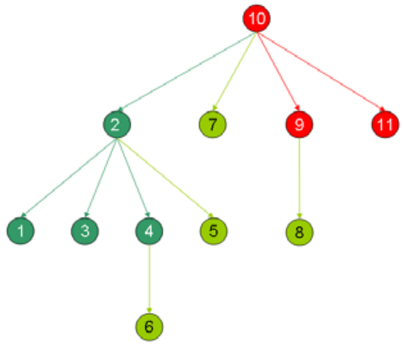

Figure 14: Shortest path starting from TEU (threshold R=0.8)

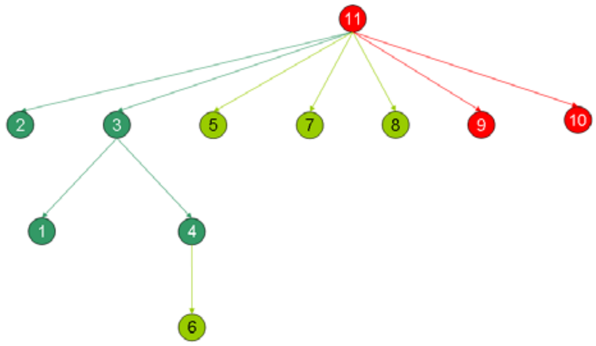

Figure 15: Shortest path starting from containers tonnage (threshold R=0.70)

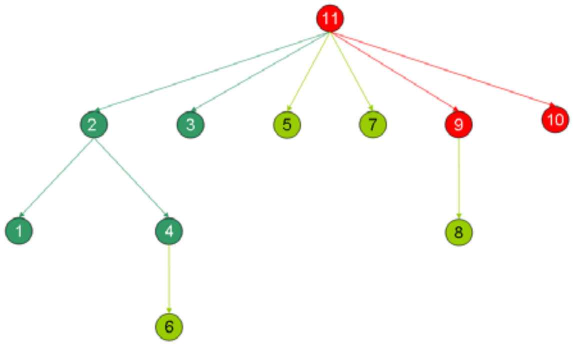

Figure 16: Shortest path starting from containers tonnage (threshold R=0.80)

The value of input (production) parameters available for year 2007 are showed in table 2.

Table 2: Production parameters in year 2007

Handled containers	323.708
Handled TEU	500.000
Handled Containers tonnage	6.677.350

On the basin of the defined shortest paths have been determined the dimensional and equipment parameters (tables 3 to 8).

This allows the comparison with the real observed values in order to validate the model.

Table 3: Parameters estimated starting from numbers of containers (R>0.80)

Parameters	Estimated value	Real value	Δ %
Quay length [m]	1.244	1.430	-13
Total stocking area [m^2]	363.319	412.000	-12
Covered stocking area [m^2]	373.555	0	-
Uncovered stocking area [m^2]	180.084	0	-
Gantry cranes [n]	8	8	0
Other cranes[n]	4	0	-
Storage cranes [n]	26	8	228
Various loaders [n]	41	20	106
TEU [n]	513.687	500.000	3
Tonnage Lo-Lo [t]	5.252.670	6.677.350	-21

3.5. Remarks

The analysis of the model application results have been synthetically reproduced for the main dimensional and equipment parameters (quay length, total storage area and number of gantry cranes) in figures 17, 18 and 19.

Table 4: Parameters estimated starting from TEU (R>0.80)

Parameters	Estimated value	Real value	%
Quay length [m]	1.077	1.430	-25
Total stocking area [m^2]	244.250	412.000	-41
Covered stocking area [m^2]	280.601	0	-
Uncovered stocking area [m^2]	-2.767	0	-
Gantry cranes [n]	6	8	-19
Other cranes [n]	1	0	-
Storage cranes [n]	16	8	99
Various loaders [n]	41	20	104
Containers Lo-Lo [n]	315.784	323.708	-2
Tonnage Lo-Lo [t]	4.685.331	6.677.350	-30

Table 5: Parameters estimated starting from containers tonnage (R>0.80)

Parameters	Estimated value	Real value	%
Quay length [m]	1.468	1.430	3
Total stocking area [m^2]	523.757	412.000	27
Covered stocking area [m^2]	460.417	0	-
Uncovered stocking area [m^2]	107.526	0	-
Gantry cranes [n]	10	8	21
Other cranes [n]	9	0	-
Storage cranes [n]	26	8	225
Various loaders [n]	232	20	1059
Containers Lo-Lo [n]	411.525	500.000	-18
TEU [n]	697.085	323.708	115

Table 6: Parameters estimated starting from numbers of containers (R>0.70)

Parameters	Estimated value	Real value	%
Quay length [m]	1.244	1.430	-13
Total stocking area [m^2]	363.319	412.000	-12
Covered stocking area [m^2]	373.555	0	-
Uncovered stocking area [m^2]	180.084	0	-
Gantry cranes [n]	8	8	0
Other cranes [n]	4	0	-
Storage cranes [n]	26	8	228
Various loaders [n]	41	20	106
TEU [n]	513.687	500.000	3
Tonnage Lo-Lo [t]	5.252.670	6.677.350	-21

Table 7: Parameters estimated starting from TEU (R>0.70)

Parameters	Estimated value	Real value	%
Quay length [m]	1.066	1.430	-25
Total stocking area [m^2]	244.250	412.000	-41
Covered stocking area [m^2]	280.601	0	-
Uncovered stocking area [m^2]	98.152	0	-
Gantry cranes [n]	7	8	-16
Other cranes [n]	8	0	-
Storage cranes [n]	16	8	99
Various loaders [n]	51	20	155
Containers Lo-Lo [n]	315.784	323.708	-2
Tonnage Lo-Lo [t]	4.685.331	6.677.350	-30

Table 8: Parameters estimated starting from containers tonnage (R>0.70)

Parameters	Estimated value	Real value	%
Quay length [m]	1.468	1.430	3
Total stocking area [m^2]	523.757	412.000	27
Covered stocking area [m^2]	460.417	0	-
Uncovered stocking area [m^2]	107.526	0	-
Gantry cranes [n]	10	8	21
Other cranes [n]	9	0	-
Storage cranes [n]	26	8	225
Various loaders [n]	37	20	86
Containers Lo-Lo [n]	411.525	500.000	-18
TEU [n]	697.085	323.708	115

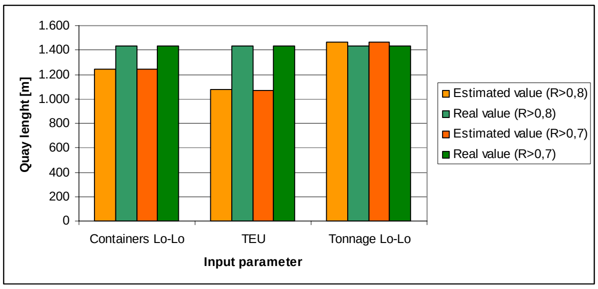

Figure 17: Estimated and real values of quay lengths for different input parameters

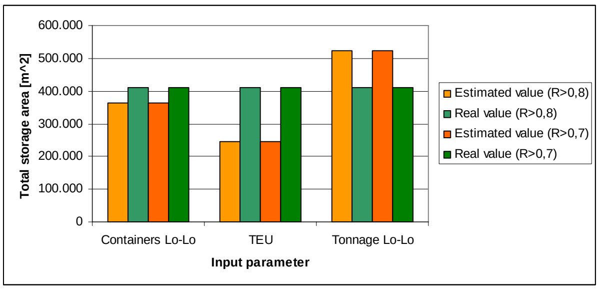

Figure 18: Estimated and real values of total storage for different input parameters

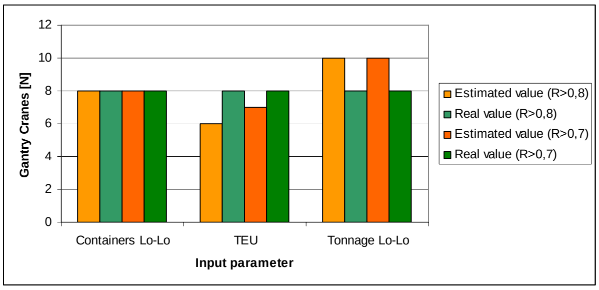

Figure 19: Estimated and real values of number of gantry cranes for different input parameters

The following considerations may be drawn:

1. the most reliable results are those related to quay length, total stocking area and gantry cranes number; the other parameters are in fact strongly influenced by local organisational issues and less suitable to be managed in a generalised approach;
2. the value of estimated parameters with the 0.7 and 0.8 threshold values are similar; therefore it may be considered not relevant on the results the choice of this threshold;
3. the number of handled containers seem to be more reliable than TEU and their tonnage as input values: in fact TEU value is not completely representative of container movements within the terminal;
4. the estimated dimensional requirements seem to be satisfied in the present situation, as well as the existing equipment seem to be just corresponding the minimum requirements.

Of course more detailed operational feedbacks may be derived by the application of the container terminals operation stochastic model.

4. CONTAINER TERMINALS OPERATION STOCHASTIC MODEL

The transit time of the generic transport unit through these terminals (TTR) represents one of the most relevant terminal performances and at the same time a key component of the freight transport generalized cost.

The TTR is composed by deterministic and stochastic components, which increases significantly the problem complexity.

The authors developed an original model based on the queuing theory allowing the calculation of the total transit time (TTR) of the single freight transport units through the terminals.

The model is applicable to a large variety of terminals.

Here its application to rail maritime terminals (sea-rail interchanges in ports) is performed and the results obtained in a real application are described.

After a synthetic description of the model structure, a methodological approach based on real collected data taking into account the influence of the following relevant parameters affecting the quality of the results is exposed:

- different typologies and sizes of intermodal units;
- additional unit movements due to co-existence of empty and full unit flows.

4.1. Methodological approach

The analysed model is based on the following minimum total transit time (TTR) definition: "time period from the arrival of the single (and generic) freight unit to the terminal gate from an external transport system (e.g. by ship) to its exit from the terminal towards a different transport infrastructure (e.g. by train)".

Obviously it does not take into account further stocking periods due to commercial reasons, which normally cause longer dwell times (sometime hundreds of hours).

The second step is the formalisation of the model finalised to the determination of the transit time.

The model concept is the decomposition of the terminal activities in a sequence of operations performed on the generic freight unit.

The single operations have been analysed into details and for each of them have been identified:

- an Operational Phase (OP) and a previous Waiting Phase (WP);
- the corresponding durations, Operation Time (TO) and Waiting Time (TW).

The following list shows the single phases, which have been identified for the most general cases:

1. Waiting before entering the terminal + Entering movement;
2. Waiting before check-in + Check-in operations;
3. Waiting before the first units transfer + First units transfer;
4. Waiting before the second unit transfer + Second units transfer;
5. Waiting before check-out + Check-out;
6. Waiting before exiting the terminal + Exiting movement.

In the generic maritime terminal the classes of entering and exiting vehicles to be considered are three (V', V'', V''') and they may allow the transport of very different amounts (NU', NU'', NU''') of freight units.

In the rail maritime terminals is NU'''(truck) < NU'(train) < NU''(ship).

Opposite flows of freight units entering and exiting on V', V'' and V''' may be accordingly identified (figure 20).

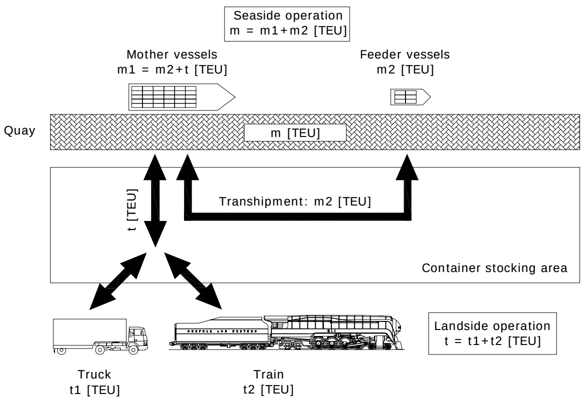

Figure 20: Freight unit flows in a generic maritime container terminal

4.2. Minimum total transit time calculation

In figure 21 are represented the duration of the single phases and the mean total transit times for the freight units running in both the directions (TTR′ and TTR″) in a generic maritime terminal.

The figure shows an imaginary space-time diagram where the operations performed within the terminal are considered in sequential order: the yellow line represents the generic freight unit entering on a vehicle V' (train) runs on it towards the transfer area and, after the stocking phase, proceeds on the vehicle V'' (ship); similarly the red line represents the generic freight unit entering on V'' and exiting on V'.

According to the units flows within the plant represented in figure 22, the transit time may be formalised as follows:

$$TTR' = \sum_{i=1}^{4} TW'_i + \sum_{i=1}^{4} TO'_i + \sum_{i=5}^{6} TW''_i + \sum_{i=5}^{6} TO''_i \qquad (8)$$

$$TTR'' = \sum_{i=1}^{4} TW''_i + \sum_{i=1}^{4} TO''_i + \sum_{i=5}^{6} TW'_i + \sum_{i=5}^{6} TO'_i \qquad (9)$$

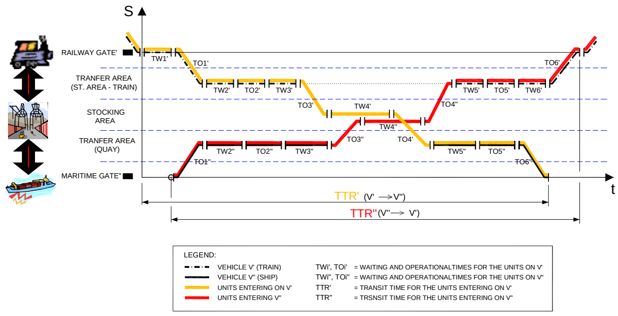

Figure 21: Single phases duration and total transit time in a generic maritime terminal

Equations (8) and (9) clearly show that the model structure can be adapted to many kinds of intermodal terminals due to the modularity of its formalisation.

The waiting times (TWi) represent the stochastic portions of the TTR and are calculated by an application of the queuing theory; the operational times descend from the schematic representation of the single activities within the terminal.

4.3. Unit size variability

An aspect affecting the sensitivity of the model results is the presence in the terminal of different sized transport units; in fact with the same quantity of Twenty feet Equivalent Unit (TEU) it is possible to handle a different number of intermodal transport units (ITU).

The EIA (European Intermodal Association), on the basis of extended investigations, suggests the following conventional equivalence between TEU and ITU:

$1{,}4\ ITU = 2{,}3\ TEU \Rightarrow 1\ ITU = 1{,}6\ TEU$

On this basis figure 22 shows two typical situations that can occur in the terminal: case b (corresponding to the EIA conventional value) is easier to work because the transhipping device can transfer the same freight quantity with less handled units than in case a (100%TEU).

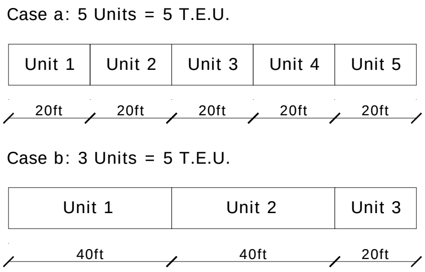

Figure 22: TEU – ITU correspondence.

Accordingly to these observations, the TTR is expected to decrease when the TEU / ITU ratio increases.

Table 9 shows a set of data collected at the Terminal Darsena Toscana in Livorno port related to the period from 1/1/2007 to 1/7/2007.

Table 9. TEUs export traffic exchange at Terminal Darsena Toscana

TEU/ITU				
Export traffic	ITUs [n]	TEUs [n]	TONS [t]	TEUs/ ITUs
	61593	92881	1189563	1,51

The two diagrams of figure 10 represent the linear interpolations to calculate the average empty weight (*Ew*) and the average full weight (*Fw*) of the units handled within the terminal on the basis of the value

4.4. Empty units management

Another important aspect to be considered in the future model applications is represented by the additional unit movements due to co-existence of empty and full unit flows. A simple methodology to calculate empty units percentage is described below.

Table 9 shows a set of data collected at the Terminal Darsena Toscana – Livorno Port related to the period January-June 2007.

Table 9. TEUs export traffic exchange at Terminal Darsena Toscana

TEU/ITU				
Export traffic	ITUs [n]	TEUs [n]	TONS [t]	TEUs/ ITUs
	61593	92881	1189563	1,51

The diagrams of figure 22 and 23 represent the linear interpolations to calculate the average empty weight (*Ew*) and the average full weight (*Fw*) of the units handled within the terminal on the basis of the *TEU/ITU* value.

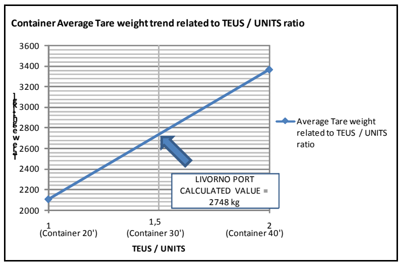

Figure 22: Determination of mean unit tare weight

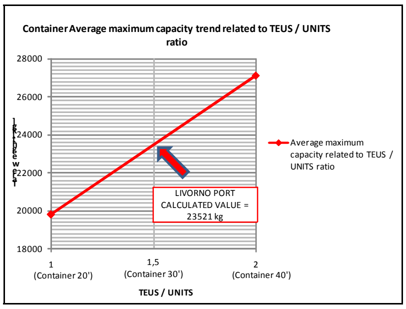

Figure 23: Determination of mean unit capacity weight

From table 9:

- total weight = 1.189.563 [t], N_{TOT} = 61.593 (total number of handled units);
- from figures 22 and 23 *TEU/ITU* = 1,51 $\Rightarrow E_W$ = 2,75 [*t*], F_W = 23,52 [*t*];
- the calculation allows to determine the empty units percentage %(e) = 20,22%.

4.5. Model application

In figure 24 and 25 is reported a graphic representation of the model application results to Livorno maritime terminal on the basis of the collected data.

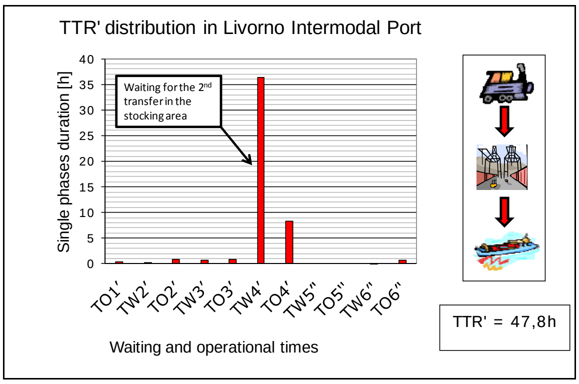

Figure 24: Model application results – Livorno Port (unit entering on train, exiting on ship).

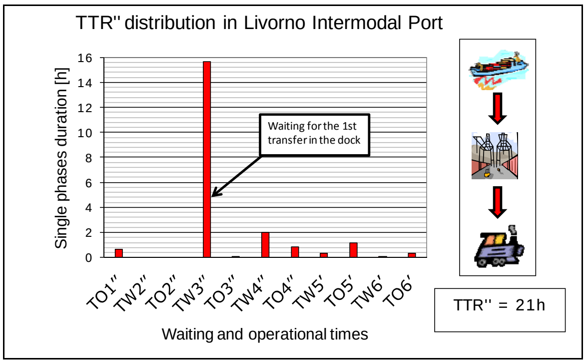

Figure 25:. Model application results – Livorno Port (unit entering on ship, exiting on train).

The analysis of the numerical values of the single time components calculated by the model leads to the following considerations:

- for the units entering by train and exiting by ship:
  1. the waiting for the second transfer in the stocking area (TW4') is largely the most extended within the terminal (about 76% of the global transit time); it depends on the mean time between 2 arriving ships;
  2. other important time period is the operation of the second transfer (TO4'), mainly due to the large quantity of transport units to be loaded on the ship;
- for the units entering by ship and exiting by train:
  1. the waiting for the first transfer in the dock area (TW3") is the longest period (about 75% of the global transit time), mainly depending on the large quantity of units to be unloaded from the ship;
  2. other important time period is the waiting for the second transfer in the stocking area (TW4"), mainly influenced by the mean time between 2 arriving trains.
- the waiting times are largely higher (86÷89% of TTR) than the operational ones.

Figure 26 and 27 show the TTR' and TTR" sensibility to the TEU/ITU ratio variation.

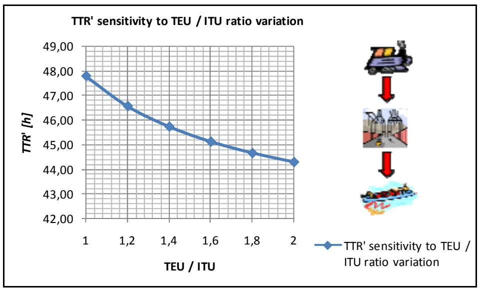

Figure 26: TTR' sensitivity analysis to the TEU / ITU ratio variation.

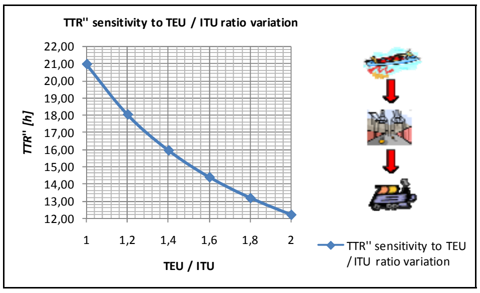

Figure 27: TTR" sensitivity analysis to the TEU / ITU ratio variation.

The figures indicate an appropriate reduction of the TTR values when the ratio increases (less handled transport units with the same freight quantity).

In the border case (only 40' units handled, that means TEU/ITU = 2), TTR' and TTR" would reduce their value by about 7% and 41% respectively.

TTR" is strongly influenced by TW3" (waiting for the first transfer from the ship to the dock and to the stocking area) also directly depending upon the number of transport units to be unloaded from the ship (it practically depends upon TEU/ITU variation).

4.6. Remarks

The model is characterised by wide generality and applicability to different terminal typologies, lay-outs, dimensions and transfer technologies.

It allows to highlight contributions and weights of the various activities and phases of the freight unit transit through the terminal by distinguishing operational and waiting periods, whose duration depends not only upon internal performances (technologies, dimensions and operational rules) but also upon external parameters and constraints (time distribution of vehicles arrivals and departures)

At present the authors are continuing model experimentation on maritime terminals in order to consolidate the methodological approach and to fine tune the most relevant parameters by means of the comparison with collected data in various operational contexts.

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