Sizing of a 3,000,000t bulk cargo port through discrete and stochastic simulation integrated with response surface methodology techniques

L. Cassettari, R. Mosca, R. Revetria, F. Rolando

Abstract**—**The purpose of the study is to size, by means of a discrete and stochastic simulator, a bulk cargo port for the unloading of coal to cover the annual requirements of a thermal power plant located next to the berth. The logistics system under consideration had to be designed so that it could ensure the supply of enough coal for the operation of the plant while reducing the overall operating costs of the system (freightage, demurrage for delays in unloading operations, investment costs, overheads) to a minimum. Thanks to Design of Experiments (DOE) and Response Surface Methodology (RSM), it was possible to determine the mathematical relationship, in the form of regression meta-model, existing between the design variables and the target function consisting in the overall annual operating cost. After the sizing it has been finally done an analysis of the strength of the identified solution as the needs for coal on the part of the power plant, with a specific reference to the capacity of the intermediate accumulation tank which constitutes a critical element in the design of this type of plants.

Keywords**—**Bulk Cargo Port Design, Discrete and Stochastic Simulation, Mean Square Pure Error Evolution, Response Surface Methodology

I. INTRODUCTION

THE installation of a new thermal power plant close to the sea makes it necessary the sizing of a bulk cargo port for the unloading of the coal to feed the steam production plant.

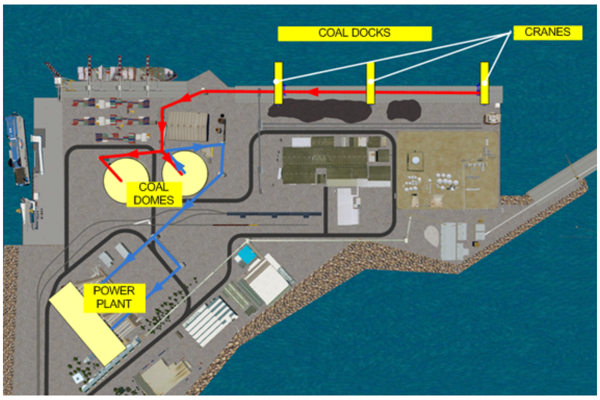

Fig. 1

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On the basis of a financial plan which takes into consideration, on one side the demurrage costs and on the other side the costs linked to the investment and to the management of the site, we have arrived to the optimal design of the following elements:

1) Number of docks;
2) Mix of incoming ships;
3) Number and capacity of berth grab cranes;
4) Capacity and number of domes used.

The presence of stochastic variables linked to the ships' interarrival laws, to the breakdowns and to the maintenance of the different installations present in the unloading and transportation system have made it necessary to undertake the study with the construction of a discrete and stochastic simulation model. The software used to build the model is Flexsim 5.0.4 by Flexsim Software Products, Inc.

II. MODEL DESCRIPTION

In the plant under study, coal is shipped by means of bulk carriers of different tonnage and from different places in the world; it is unloaded by means of port unloading equipment (grab cranes) that feeds a system of conveyor belts, which carry the coal to an intermediate storage system (domes) and/or feed it to the furnace bunkers serving the plant. Figure 1 shows the plan of the complex as described in the simulation model.

As far as the main port infrastructures are concerned, the model calls for a quay with a maximum length of 650 m., which could allow the simultaneous berthing of 2 ships of the Capesize type, provided the water depth allows it. The length of the quay in the simulation tests will be linked to the type of scenario under analysis (one or two berths) as it will be explained hereinafter.

The unloading infrastructures envisage a maximum of no.3 grab cranes of the type with a fixed winch and raisable arm, with a free-digging unloading rate that is a settable working parameter of the model, depending on the scenarios under consideration.

The intermediate storage system is made up by circular covered tanks, called "domes", the maximum capacity of which is a settable parameter of the model; the function of such tanks is to guarantee the continuous supply of the power station. The choice to utilize the "domes" as coal tanks originates from the current requirements of a covered storage imposed by the environmental regulations.

The flows of the materials in the model are as follows:

- Coal: the ships that berth at the coal unloading quay are unloaded by the quay grab cranes according to procedures that are explained hereinafter. The unloaded coal is transferred to the tanks ("domes") by means of a system of covered conveyor belts. The coal is then collected from the dome automatically and loaded onto a system of outgoing conveyor belts which takes it up to the boiler bunkers of the power station.

- By-products: in addition to the coal, there are secondary flows of by-products of the power station. The by-products under consideration are: ash, gypsums and limestone.

The methods of transport of the by-products are listed in Table I:

Material	*Transport*
Ash	Ship
Gypsums	Truck
Limestone	Train

Table I

A. The ships

In the model we have used the following standard types of ocean-going vessels:

- Barge;
- Handysize;
- Panamax;
- Capesize;

The Table II shows the main features of the type of vessels listed here above:

Type	*DWT [t]*	*Holds number*	*Lenght [m]*	*Width [m]*	*Draft [m]*
Barge	5.000	2	135	16	-
Handysize	20.000	4	165	24	9
Panamax	60.000	5	228	30.6	12
Capesize	79.800	7	282	34	18

Table II

The ships' mix, that is the share of coal transported by the various types of ship, influences the performances of the system in terms of:

1) freight costs, which are in inverse relation to the transported quantity of coal (DWT);
2) demurrage days, which are in direct relation to the tonnage;
3) dredging works and the sea bottom, which restrain the types of ship that can dock;
4) number and unloading logics of the harbour cranes.

The cargo in each hold is made up by a number of discrete units (flowitems) obtained by the ratio between the tonnage contents of the hold and the capacity of the bucket of the grab crane (a parameter that can be set by GUI).

This solution has been adopted in order to be able to replicate the correct unloading of the ships; this way in fact the grab cranes execute a number of cycles equal to the number of "bucket-loads" necessary to unload a ship.

The unloaded flowitems are later converted into fluid units by a specific object (itemtofluid), which, for each unloaded discrete unit, generates a number of fluid units equal to the capacity of the bucket.

The number of ships has been calculated on the basis of the yearly coal needs of the power station, of the DWT and of the mix utilized. Given:

- Ci ($1 \leq i \leq 4$): the capacity of the ships for each type;
- Ctot: the yearly coal needs;
- a, b, c, d: the percentages to be utilized for each type of ships;

the yearly number of ships, for each type (Ni) results from solving the following linear system:

$$\begin{pmatrix} C1 & C2 & C3 & C4 & 0 \\ 1 & 0 & 0 & 0 & -a \\ 0 & 1 & 0 & 0 & -b \\ 0 & 0 & 1 & 0 & -c \\ 0 & 0 & 0 & 1 & -d \end{pmatrix} \bullet \begin{pmatrix} N_1 \\ N_2 \\ N_3 \\ N_4 \\ N_{TOT} \end{pmatrix} = \begin{pmatrix} C_{tot} \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

(1)

Once the number of ships has been determined, we then calculate the average interarrival time.

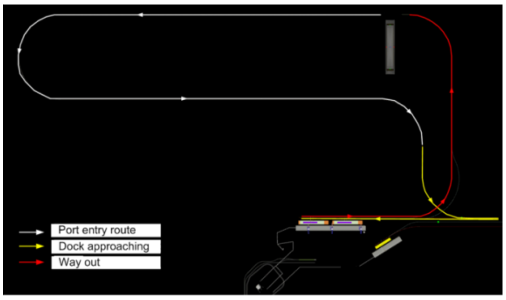


Fig.2

In order to represent the law of the interarrival of the ships, we have chosen to use distributions of the Beta type with an average equal to the average interarrival time calculated above. From the model point of view, each type of ship is generated by an object of the Source type and sent to an object (queue) located outside the harbour, inside which the ship stays until a berth becomes free. This way it is possible to easily measure the waiting time for each type of ships which will have an impact on the cost of the demurrage.

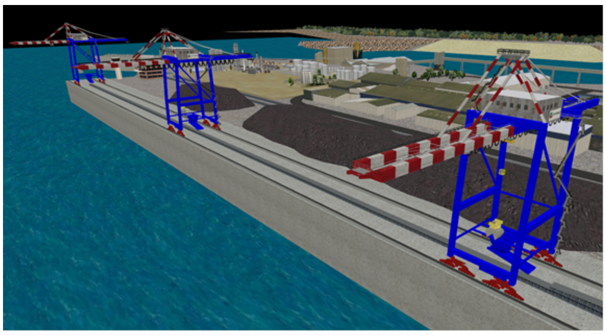


Fig.3

The ships travel at three different speeds, as represented in Figure 2: a cruising speed, which they keep during the travelling routes and going out of the harbour, a manoeuvring speed, which they keep while entering the harbour, and a berthing speed, which they keep in the last stretch of their route, a last stretch orthogonal to the quay, set in such a way as to simulate the berthing time.

B. The grab cranes

The unloading infrastructure envisages a maximum of no.3 grab cranes of the type with a fixed winch and raisable arm, as shown in Figure 3, with an unloading rate which can be set as a working parameter of the model.

The effective unloading rate is a function of the "free-digging" rate, that is the theoretical unloading rate that can be obtained under maximum efficiency conditions, according to the following reduction coefficients:

- Opening time of the hold hatches: 0.85
- Weather conditions: 0.95
- Emergency maintenance (breakdowns): 0.95
- Holds cleaning: 0,85
- Yield in filling the bucket: 0.92.

Therefore the effective rate comes to about 60% of the "free-digging" rate.

In order to implement this logic into the model it has been necessary to carry out a series of experiments to measure the cycle time for different settings of some parameters. In consideration of the importance of the grab cranes, we have chosen to create ad hoc objects that could reproduce faithfully the movements of the cranes and the respective action times.

Such objects offer the possibility of obtaining different cycle times acting mainly on only two factors: the bucket capacity, that is the tons/cycle unloaded at each trip, and the four typical speeds (the crane transverse motion speed, the trolley speed, the lifting speed and the descent speed). To set the different simulation scenarios we have chosen, once the bucket capacity has been set, to keep unchanged the crane translation and trolley speeds and to derive a relationship linking the downloading rate and the lifting speed.

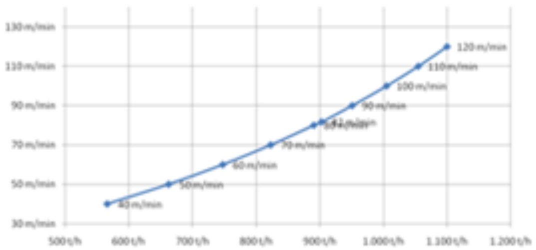


Fig.4

Such relationship is shown in the Figure 4 diagram.

As the bucket capacity varies, the descent rate varies according to the Figure 5 diagram.

The logic supporting the operational modes of the grab cranes is, without a doubt, the most complex part of the entire model, since we have tried to replicate as faithfully as possible such movements.

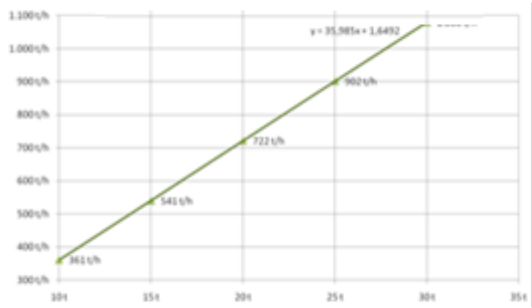


Fig5

The movements and the manners by which the cranes approach the different ships have been implemented in an object called "decider".

The decider has been programmed by specific algorithms in c++ in order to optimize the assignment of the cranes to the ships and the quays.

The underlying logics are affected by the following variables:

1) number of active grab cranes: from 1 to 3;
2) number of active berths: 1 or 2;
3) type of ship showing up in the harbour;

For problems of overall dimensions of the grab cranes and of the relative size of the vessels, there is a maximum number of grab cranes that may work at the same time on the same ship: 1 on Barge , 2 on Handysize, 3 on Panamax and Capesize.

A further constraint that has been implemented in the decider code provides that two grab cranes may not operate at the same time on adjoining holds. Taking into account that the operation of the unloading system may be configured by setting the number of active berths (1-2) and grab cranes (1-2-3), here is the list of all the possible configurations:

1) **1 berth – 1 grab crane**
   This is the simplest scenario in which, in the presence of a ship, the grab crane starts its work by unloading the first hold and then proceeds moving on to the next hold and so on.
2) **1 berth – 2 grab cranes**
   In case of a barge the procedure is the same as in the previous case; in case of a larger ship, however, the two grab cranes follow the scheme of figure 6: they start unloading the holds on both ends and then converge towards the centre until only two adjacent holds remain; at that point one of the two grab cranes (P2) moves into rest position and the other one completes the job.

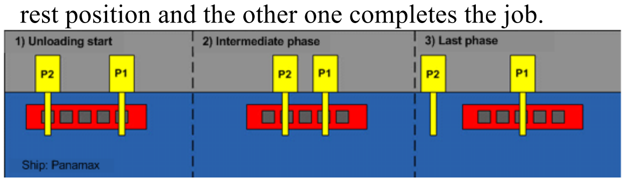


Fig.6

3) **2 berths – 2 grab cranes**
   When only one of the two berths is occupied the unloading procedure is the one described in case b); if a second ship enters the harbour, the grab crane closer to the second berth moves over to unload such ship
4) **2 berths – 3 grab cranes**
   For the ships which, due to their characteristics, may be

served only by one or two grab cranes simultaneously, the procedures described for the previous cases apply. The Panamax and Capesize type ships, thanks to their size, may be served by three grab cranes simultaneously; in these cases the initial setting includes two grab cranes (P1 and P3) at the ends and one (P2) at the centre of the ship, as shown in Figure 7. P1 and P3 move converging towards the central hold, while P2 moves over to the holds adjacent to the one just emptied; all this takes place always by respecting the constraint that two grab cranes cannot work on two contiguous holds. If there are not enough holds, placed so as to allow the simultaneous work of three grab cranes, one of the external ones (P1 in case of berth 2 and P3 in case of berth 1) moves into rest position and lets the other two finish the work. When two ships arrive at the same time, each one is assigned automatically one of the two external grab cranes (P1 or P3), while P2 is assigned to the larger ship. P2 moves over to the other quay in case an even larger ship arrives, or if the ship on which it is working has no more room to allow the simultaneous work of two grab cranes. Finally, it is to be noted that the model does not contemplate the use of three grab cranes in the configuration with a single berth, because such situation would give rise to unjustified costs, given the low utilisation rate that would result for each grab crane.

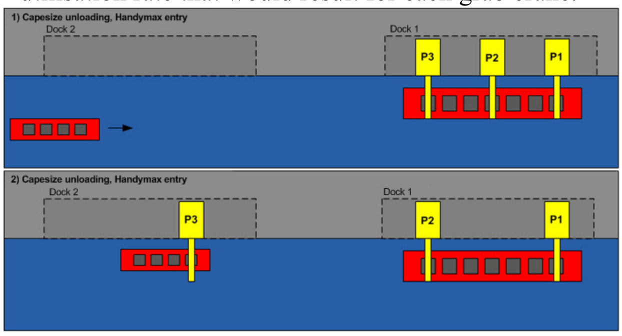


Fig.7

C. Transport and storage systems

The grab cranes are equipped with an internal hopper which conveys the coal onto the conveyor belts of the quay, which transfer the material up to the storing area.

The conveyor belt system must ensure therefore the transfer of the coal from the unloading quay to the dome and from there to supply the power station (from the dome to the boiler bunkers).

It is made up by 16 segments with a total length of ~2,300 m (a calculation made by assuming the use of two domes) in case two berths are activated, while it is a little shorter, about 2,000 m, in case the activation of only one berth is chosen. Fig. 8 shows in detail the calculation of the total length of the conveyor belt system in case of a single berth:

Dock:		530 m
Dock to dome 1:		
	1st part	130 m
	2nd part	100 m
	3rd part	74 m
		304 m
Dome 1		
	conveyor IN/OUT (2x48m)	96 m
		96 m
Dome 2		
	conveyor IN/OUT1 (2X135m)	270 m
	conveyor IN/OUT2 (2x48m)	96 m
		366 m
Dome 1 to power plant:		
	1st part	135 m
	2nd part	72 m
	3rd part	215 m
	4th part	98 m
		520 m
Power plant conveyors:		
	1st part	220 m
	2nd part	220 m
		440 m
	TOTAL:	2256 m

Fig.8

The capacity of the conveyor belts feeding the dome has been set at 3,000 t/h, that is equal to 10% more than the maximum unloading rate that can be achieved by the simultaneous use of 3 grab cranes. Such overscaling is justified by the need that the grab cranes always have the possibility of working, avoiding congestions with the consequent stoppage of the unloading operations.

The capacity of the conveyor belts feeding the power station has been set at 500 t/h, in order to guarantee the daily supply of the coal needed by it.

Such capacities refer to the assumption in which the yearly coal requirement of the power station is of 3,000,000 t. The conveyor belt system assumes the use of 9 towers in order to take into account the deviations and the gradients of the belts required by the layout.

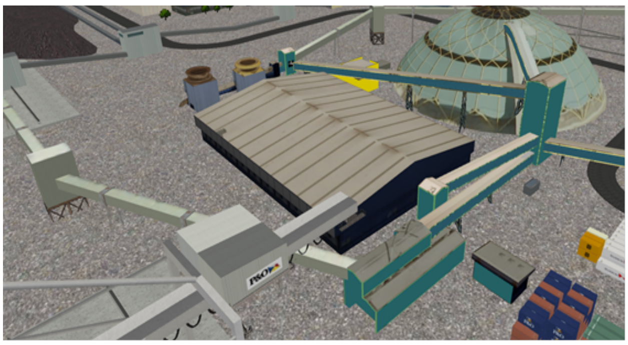


Fig.9

The chosen storing solution requires the realization of one or more circular covered areas with geodetic cover of the “Dome" type, as shown in figure 10. As explained hereinafter, the choice of the storing capacity will be a parameter that will affect strongly the performance of the system.

Fig.10

Inside the domes there are stackers-reclaimers, machines that allow stacking and reclaiming the coal in a fully automated way.

The capacity of such stackers-reclaimers is as follows:

- stacking: 3,000 t/h
- reclaiming: 1,000 t/h

The model allows setting the initial content and the maximum capacity of the storing system. The assessment of the initial content is made on the basis of the power station consumption and of the arrival time of the first ship.

The code in the model also envisages that, in case the content of the domes reaches 98% of the set maximum capacity, the unloading of the coal is suspended.

When the content goes below ≤ 80% of the maximum capacity, the unloading is reactivated and the grab cranes start working again.

Such considerations show the importance of the correct sizing of the dome; the stoppage of the harbour due to a collapse of the storing system is a condition that must be avoided at any cost, since, should it happen, the efficiency of the system would be heavily compromised.

III. Settings of the Analysis Phase

ANOVA and Response Surface Methodology [6] techniques are utilized in the model analysis phase in order to identify the optimal port configuration.

The target function that we want to minimize is the total yearly operation cost subdivided in the following items:

1) **ships' freight**: it is the main cost item; it is linked to the type of ship, to the quantity of carried coal and to the country of provenance; it has been assumed to get the supplies from Canada, the United States, South Africa and Australia, according to the quantities shown in Table III:

Country	% of total imported coal	Coal quantity/year
Canada	15%	450,000 t/y
U.S.A.	35%	1,050,000 t/y
South Africa	30%	900,000 t/y
Australia	20%	600,000 t/y

Table III

The choice of diversification of the suppliers is a choice actually adopted, and it is dictated mainly by the fact that it would be impossible, as well as economically unprofitable, to get 100% of the required coal supplies from a single country.

The imported coal is valued in quotas that are expressed in €/t and vary, obviously, according to the country of provenance.

Table IV summarizes such values, separated according to the type of ship:

Country	Ship		
	Handymax	Panamax	Capesize
Canada	21.24 €/t	20.71 €/t	18.44 €/t
U.S.A.	15.52 €/t	15.00 €/t	12.72 €/t
South Africa	16.24 €/t	15.71 €/t	13.44 €/t
Australia	19.81 €/t	19.29 €/t	17.01 €/t

Table IV

The cost for chartering the ships will therefore be influenced by the mix of ships, that is by the % of each type of ship that will serve the harbour in each configuration. The mix will therefore be a variable to manage with extreme care, as it will be explained later.

2) **personnel costs**: the personnel can be divided in two categories: the ones assigned to the unloading and the daily staff, assigned to the complementary operations (cleaning the holds, cleaning the conveying belts, maintenance, control, and so on).
3) **maintenance costs** for the grab cranes, conveying belts, stacker-reclaimer, electric systems, lighting systems, firefighting systems;
4) **depreciation** allowances for civil constructions (20 years), grab cranes (10 years), domes (15 years), conveyor belts, towers and other facilities (10 years);
5) **demurrage**, the cost of which depends on the type of ship, according to Table V:

Ship	DWT	Demurrage
Barge	5.000 t	0 €/gg
Handysize/Handymax	20.000 t	30.000 €/gg
Panamax	60.000 t	35.000 €/gg
Capesize	79.800 t	45.000 €/gg

Table V

6) **cleaning costs** for the holds and the conveyor belts.

As already evidenced in the introduction, the project variables to dimension as a function of the operation costs are the number of berths, the number of grab cranes and their unloading rate, the ships' mix and the storage capacity of the domes.

Since the number of berths (1 or 2) also conditions, as we have already said before, the number of grab cranes, we have decided to consider this factor as a scenario variable. The final decision, therefore, will be taken by comparing the optimum solution of the first scenario with the optimum solution of the second one, and of the two we shall choose the one considered as more favourable.

The storage capacity of the domes has shown itself to be a determinant factor. often the demurrage values obtained with the simulator reached very high figures because of the frequent stops of the unloading system caused by an insufficient capacity of intermediate storage. We have therefore decided to initially set the storage capacity to infinity, and to determine afterwards the size of the dome on the base of the actual utilization demand thereof as explained further on.

Therefore the focus of the testing moves to the grab cranes and to the ships' mix for which it has been necessary to define a range of variability.

As to the grab cranes, however, we have assumed as a summary variable of their behaviour the unloading capacity, that is a combination between the unloading rate and the number of grab cranes. In particular, in correspondence of the first scenario (a single berth), the variability ranges are:

- Lower level: 1 grab crane, free-digging rate 1,500 t/h;
- Higher Level: 2 grab cranes, free-digging rate 1,900 t/h each;

While in the second scenario (two berths) they are:

- Lower level: 2 grab cranes, free-digging rate: 1,500 t/h each;
- Higher Level: 3 grab cranes, free-digging rate: 1,900 t/h each;

In both scenarios the grab cranes work for 2 shifts per day of 8 hrs each, for 5 days a week, Monday to Friday.

For the variable "ships' mix" we have assumed to consider as lower level the configuration in which there arrive mostly small ships (of the Handysize type) and as higher level the one in which there arrive bigger ships on average (Table VI).

Unlike what we have said for the grab cranes, the range of the variable "ships' mix" remains the same in both scenarios. The two ends of the range are represented by the following percentages:

Ship	Mix	
	Low level	High level
Handysize/Handymax	79,2%	16,7%
Panamax	20,8%	37,5%
Capesize	0,0%	45,8%

Table VI

A. Scenario with 1 berth

Determination of the length of the simulation run

In order to determine the optimal length of the simulation run we have applied the study methodology of the evolution of the MSPE over time [3].

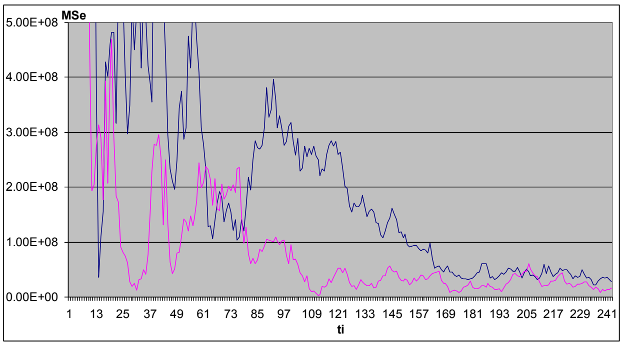


Fig.11

For building the curve, the two independent variables, the cranes capacity and the ships mix, are set at the centre level of their respective variability ranges and the experimental replications to be run are set at 4. Figure 11 shows two possible curves of the evolution of the error about the scenario with 1 berth.

As per theory, the two curves, once the error is stabilized, tend to be superimposed, consequently a length of the simulation run t0 equal to 240 months is largely satisfactory. Consequently the answer of the simulator will show an error band of the type of (2):

$$\bar{y}(t_0) - 3\sqrt{MSPE(t_0)} \le y^*(t_o) \le \bar{y}(t_0) + 3\sqrt{MSPE(t_0)} \quad (2)$$

In the case under examination, since the MSPE (240) is about 1.4·107 the bandwidth is equal to ± 11.000 €, a value that has a negligible impact on an average monthly demurrage cost of about 273,000€.

Application of the DOE and RSM techniques

In view of looking for the regression surface that suits satisfactorily the whole of the experimental points, we have set a 22 factorial project, suitable for the determination of a 1st order model.

The factors taken into consideration have been the grab cranes (Factor A) and the mix of ships (Factor B). An experimental plan has been built, made up by four top trials and four central trials. The amount of the demurrage paid in the above simulation runs are shown in table VII.

Factors levels		Average monthly demurrage	Total annual amount
Cranes	Ships mix		
B	B	€ 400.922,91	€ 4.811.074,92
A	B	€ 76.236,40	€ 914.836,80
B	A	€ 266.202,22	€ 3.194.426,64
A	A	€ 54.094,59	€ 649.135,08
A	Centr	€ 277.889,86	€ 3.334.678,32
B	Centr	€ 273.726,05	€ 3.284.712,60
Centr	B	€ 268.682,49	€ 3.224.189,88
Centr	A	€ 276.888,98	€ 3.322.667,76

Tab.VII

Once obtained the demurrage amounts, the operating costs for each configuration have then been computed by using MS Excel. Such costs have been input in the Design-Expert software.

ANOVA for selected factorial model

Analysis of variance table [Partial sum of squares - Type III]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	7.5038E+012	1	7.5038E+012	10.927	0.016295	significant
B-Mix	*7.5038E+012*	*1*	*7.5038E+012*	*10.927*	*0.016295*	
Residual	4.1205E+012	6	6.8675E+011			
Lack of Fit	*4.1071E+012*	*3*	*1.3690E+012*	*307.56*	*0.00031290*	*significan*
Pure Error	*1.3354E+010*	*3*	*4.4513E+009*			
Cor Total	1.1624E+013	7				

Fig. 12

From the analysis of the ANOVA table, shown in figure 12, it can be observed the significance of the "Lack of Fit" test which points to a lack of adaptation of the surface obtained to the experimental points.

Once the attempt to adapt to the experimental points a regression meta-model of the 1st order has failed, we have set up a central composite project with axial tests placed, for technological reasons, on the border of the validity area of the experiment.

Through the Design Expert 8.0 software by Stat-Ease, we have obtained the response surface shown in Figure 13, whose equation (3) has been validated via the double Fisher-test.

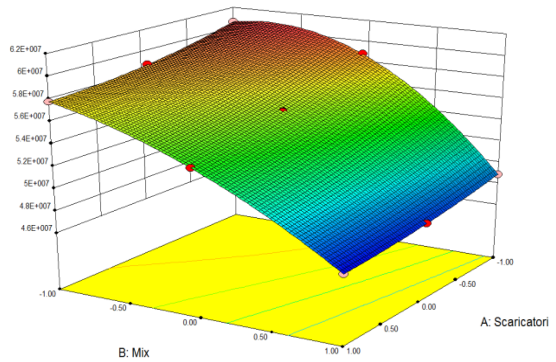


Fig.13

$$\bar{y} = 5.59 \cdot 10^7 - 2.468 \cdot 10^6 A - 5.532 \cdot 10^6 B + 2.147 \cdot 10^5 AB + 4.21 \cdot 10^5 A^2 - 2.743 \cdot 10^6 B^2 - 1.135 \cdot 10^5 A^2 B + 1.292 \cdot 10^6 AB^2 \quad (3)$$

From the analysis done, we infer the significance of both chosen factors and of their interaction; this indicates that both the unloading rate and the composition of the ships' arrivals, and the combined effect of these two factors, affect the target function under consideration.

Once the surface is known, it is possible to identify the optimal working configuration in correspondence of its minimum point which, for the scenario under consideration, corresponds to the combination with both factors set at the higher level.

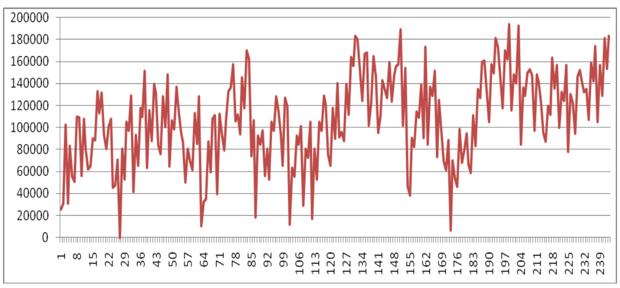


Fig.14

Please note that for the storing we have utilized two 110,000 t domes, a choice dictated by the data about the filling up of the domes as resulted by the simulation as it can be gathered by Figure 14.

Figure 15 shows the calculation of the operational costs deriving from the chosen technological configuration.

Cost	Unit	Quantity	Unit cost [€]	Total cost [€]
Freights:				**€ 40.418.571,43**
Handysize	num.	8		
Panamax	num.	18		
Capesize	num.	22		
Unloading operations staff:				**€ 502.000,00**
team leader	num.	1	€ 62.000,00	
crane operators	num.	5	€ 55.000,00	
stacker-reclaimer operator	num.	1	€ 55.000,00	
conveyors operators	num.	2	€ 55.000,00	
Other staff:				**€ 627.000,00**
department head	num.	1	€ 62.000,00	
assistants	num.	3	€ 55.000,00	
team leaders	num.	2	€ 50.000,00	
workers	num.	6	€ 50.000,00	
Maintenance:				**€ 670.000,00**
cranes	n°	2	€ 200.000,00	
belt conveyors	flat		€ 270.000,00	
Depreciation charge:				**€ 2.896.333,33**
civil works			€ 1.480.000,00	
cranes			€ 500.000,00	
domes			€ 469.333,33	
belt conveyors:			€ 447.000,00	
Demurrages:				**€ 649.135,08**
Other costs:				**€ 1.200.000,00**
holds cleaning	€/coal ton	0,3	3.000.000 t	
conveyors cleaning	€/coal ton	0,1	3.000.000 t	
TOTAL:				**€ 46.963.039,84**

Fig.15

The ships' freight represents the component with the highest impact on the total, equal to about 86% of it. It is easy to understand, therefore, how convenient it is the choice to privilege the chartering of big size ships, although such choice entails a greater investment in maritime works.

Finally, always thanks to the help of the Design Expert software, it has been possible to obtain for each interest section the tolerance interval (TI), the confidence interval on the mean response (CI) and the prediction interval (PI). Figure 16 shows the surface section corresponding to the optimum area with the variable "ships' mix" as a constant and set equal to the optimum value, that is the higher value of the variability range.

In correspondence with the optimum point (the yearly operational cost equal to 46,960,000 €) we obtain the following intervals with respect to the average value:

- 95% CI: ± 150,000 € (± 0.3%);
- 95% PI: ± 218,000 € (±0.4%);
- 99% TI: ± 400,000 € (± 0.8%).

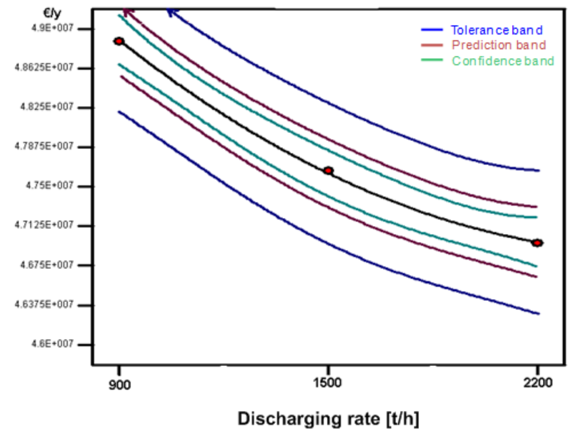
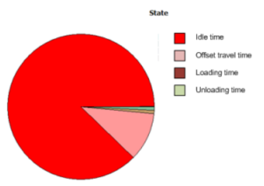
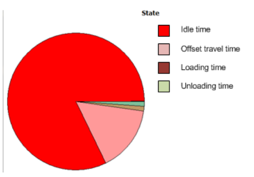


Fig.16

Thanks to the data extrapolated from the simulation model, it has been possible to calculate also the utilization rates of the quay cranes, the berth occupation rate and the average waiting time for each type of ship. The utilization rates of the two grab cranes are shown in the following pie charts:

P1 grab crane: 17.8% P2 grab crane: 12.4%





By observing these charts we can notice a very low utilization rate for both grab cranes. The utilization rates have been calculated on the basis of the ratio between actual working time and total available time of the cranes. Very low values of such indicators are due to the inter-arrival times of the ships, which are sometimes greater than two or three days; indeed the fact that the grab cranes are "idle" for most of their available time, entails a lowering of their utilization. However, the possibility of purchasing a single grab crane is excluded from the results of the analysis, according to which the saving of investing in one grab crane is not enough to compensate the other costs in terms of demurrage that would be paid due to a relevant increase in the waiting time of the ships.

As far as the occupation time of the berth is concerned, the following calculation has been made:

	Dock 1		
Ship	Average dock staying time	number of ships	Total time
Handymax	1,41 d	8	11,28 d
Panamax	2,64 d	17	44,88 d
Capesize	3,60 d	22	79,20 d
		Total time:	135,36 d
		Simulation lenght:	365,00 d
		Dock utilization index:	37,08%

Table VIII

From this calculation emerges an occupation rate such as to allow facing emergency situations in which the number of arriving ships should increase.

Also for the waiting time of the ships the identified configuration gives results:

Ship	Number of ships in the 20th year	Numbero of waiting ships	% of waiting ships on total ships	Average waiting time
Handymax	8	3	37,50%	1,58 d
Panamax	17	3	17,65%	0,53 d
Capesize	22	4	18,18%	1,58 d
Total	**47**	**10**	**21,28%**	**1,23 d**

Table IX

From the analysis it emerges, in fact, that only about 21% of the ships had to wait and that the average waiting time for each type never exceeds two days. Furthermore we can also remark that the ships that, as a percentage, had to wait longer, are of the Handysize type, and this is positive since, being the demurrage cost directly proportional to the size of the ships, the Handysize are the ones with a lesser unit cost.The resulting demurrage cost is about 650,000 €/year, a value definitely acceptable if compared to the total operating costs.

B. Scenario with 2 berths

Determination of the length of the simulation run

Also in this case we have decided to set at 4 the number of central replications. As far as the duration of such throws is concerned, we have decided to set it, as in the previous scenario, at 240 months (20 years), utilizing a data collection pace Δt of one month. Therefore also in this case the total number of collected time instants has been 243. The obtained graph is shown in Fig. 17.

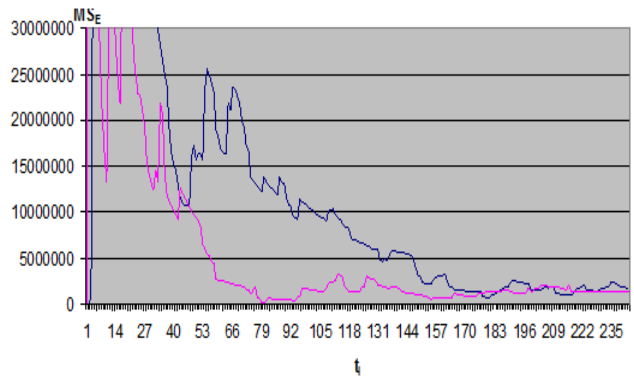


Fig.17

The convergence is evident from the 200th month; however in order to be surer about the validity of the results, we have decided to set the duration of the following throws at 240 months as in the previous scenario.

At the 240-month level of simulation, the MSPE on the normalized value of the demurrage amounts is around 1.95·106, from which:

$$\sigma = \sqrt{1{,}95 \cdot 10^6} = 1.400\,€$$

and therefore

$$\pm 3\sigma \approx \pm\, 4.200\ €$$

Considering that the average monthly demurrage in this configuration is equal to about 8,200 €. Such value would indicate an error margin quite pronounced; however, also in the presence of a maximum demurrage of 12,000 €, equal to 144,000 € yearly, such amount would be relatively not significant in comparison with operating costs around tenths of million euros.

Application of the DOE and RSM techniques

The procedure for the search of the adapting surface has started also in this case from a first order model, setting a factorial project 22; the results of the simulation throws are shown in Table X:

Factors levels		Average monthly demurrage	Total annual amount
Cranes	Ships mix		
B	B	€ 159,28	€ 1.911,42
A	B	€ 0,00	€ 0,00
B	A	€ 3.507,93	€ 42.095,19
A	A	€ 410,11	€ 4.921,38
Centr	Centr	€ 8.355,80	€ 100.269,55
Centr	Centr	€ 8.480,65	€ 101.767,85
Centr	Centr	€ 5.933,75	€ 71.205,00
Centr	Centr	€ 8.026,23	€ 96.314,79

Table X

also in this case, however, a linear model has shown not to be suited to represent the test data.

We have therefore searched for the adaptation with a second order model, via the construction of a "face centred" central composed project. The results obtained for the four additional axial tests are shown in Table XI:

Factors levels		Average monthly demurrage	Total annual amount
Cranes	Ships mix		
A	Centr	€ 3.635,76	€ 43.629,15
B	Centr	€ 13.981,00	€ 167.772,00
Centr	B	€ 392,66	€ 4.711,90
Centr	A	€ 5.670,37	€ 68.044,47

Tab. XI

The next step has been to assess the minimum storage capacity for each configuration, to choose the most suitable dome size, and to enter the cost items about the demurrage and dome depreciation in the MS Excel worksheet.

Once the operating costs have been obtained for each configuration, such values have been input in Design Expert in order to build the desired project.

The response surface obtained and the relevant equation are shown here below.

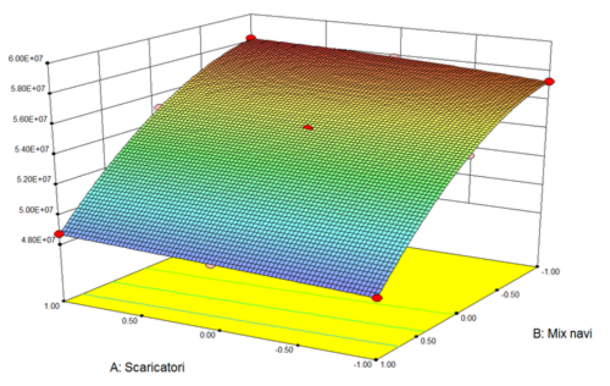


Fig.18

$$\bar{y} = 5.489 \cdot 10^{7} + 3.179 \cdot 10^{5} A - 4.761 \cdot 10^{6} B - 6.782 \cdot 10^{4} AB - 9.285 \cdot 10^{4} A^{2} - 1.75 \cdot 10^{6} B^{2} + 6.994 \cdot 10^{4} A^{2}B + 8.996 \cdot 10^{4} AB^{2} \quad (4)$$

In this case the "Lack of Fit" test is not significant, therefore the obtained model is suited to represent the link existing between the dependent variable and the independent ones. From the ANOVA analysis, shown in figure 19, we can remark also the fact that both A and B factors are significant, in particular B; in other words the "ships mix" variable seems to be the factor with the greatest impact on the answer, a factor that results significant both as term of the first order and of the second order.

Analysis of variance table [Partial sum of squares - Type III]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	1.438E+014	7	2.054E+013	14955.76	< 0.0001	significant
A-Scaricator.	*2.022E+011*	*1*	*2.022E+011*	*147.22*	*0.0003*	
B-Mix navi	*4.533E+013*	*1*	*4.533E+013*	*33008.41*	*< 0.0001*	
AB	*1.840E+010*	*1*	*1.840E+010*	*13.40*	*0.0216*	
A²	*2.286E+010*	*1*	*2.286E+010*	*16.65*	*0.0151*	
B²	*8.167E+012*	*1*	*8.167E+012*	*5947.34*	*< 0.0001*	
A²B	*6.523E+009*	*1*	*6.523E+009*	*4.75*	*0.0948*	
AB²	*1.079E+010*	*1*	*1.079E+010*	*7.86*	*0.0486*	
Residual	5.493E+009	4	1.373E+009			
Lack of Fit	*4.878E+009*	*1*	*4.878E+009*	*23.83*	*0.0164*	*not significant*
Pure Error	*6.142E+008*	*3*	*2.047E+008*			
Cor Total	1.438E+014	11				

Fig.19

In this case the minimum surface is obtained in correspondence of a low level of the "grab cranes" variable and a high level of the "ships mix" variable. Therefore the optimum configuration of the harbour system in the scenario with two active berths, will be obtained in correspondence of the purchase of only two grab cranes, with a 1,500 t/h free-digging rate each, and steering the ship chartering towards a majority of large-size ships.

The confidence bands calculated in correspondence of the optimal region are shown in figure 20.

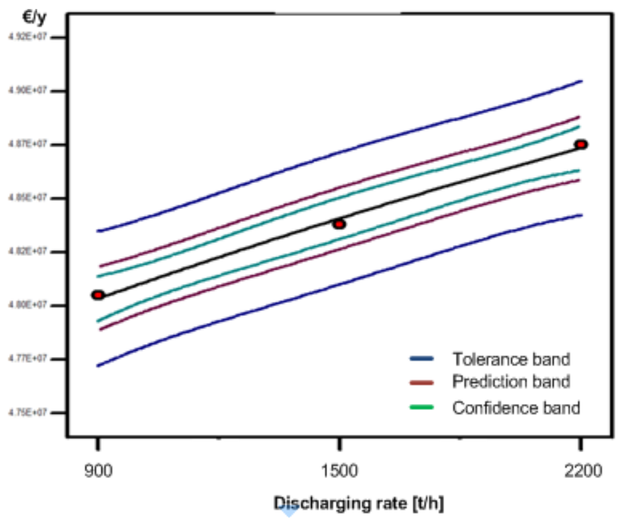


Fig.20

In correspondence with the optimum point (the yearly operational cost equal to 48.033.000 €) we obtain the following intervals with respect to the average value:

- 95% CI: ±160.000 € (±0.3%);
- 95% PI: ± 230.000 € (±0.5%);
- 99% TI: ± 480.000 € (±1%).

The details of the operating costs by individual items are shown in figure 21.

Cost	Unit	Quantity	Unit cost [€]	Total cost [€]
Freights:				**€ 40.418.571,43**
Handysize	num.	8		
Panamax	num.	18		
Capesize	num.	22		
Unloading operations staff:				**€ 502.000,00**
team leader	num.	1	€ 62.000,00	
crane operators	num.	5	€ 55.000,00	
cker-reclaimer operator	num.	1	€ 55.000,00	
conveyors operators	num.	2	€ 55.000,00	
Other staff:				**€ 627.000,00**
department head	num.	1	€ 62.000,00	
assistants	num.	3	€ 55.000,00	
team leaders	num.	2	€ 50.000,00	
workers	num.	6	€ 50.000,00	
Maintenance:				**€ 670.000,00**
cranes	n°	2	€ 200.000,00	
belt conveyors	flat		€ 270.000,00	
Depreciation charge:				**€ 4.574.166,67**
civil works			€ 2.806.500,00	
cranes			€ 400.000,00	
domes			€ 682.666,67	
belt conveyors:			€ 685.000,00	
Demurrages:				**€ 42.095,19**
Other costs:				**€ 1.200.000,00**
holds cleaning	€/coal ton	0,3	3.000.000 t	
conveyors cleaning	€/coal ton	0,1	3.000.000 t	
TOTAL:				**€ 48.033.833,28**

Fig.21

The schedule shows a significant increase in the depreciation charges of the civil works following an increase of the investment costs up to 77,220,000€. Compared to scenario 1, in fact, the differences are:

- dredging: it is necessary to have a larger deep waters area to make one more berth available.
- quay: it is twice as long as the previous one, with the consequent increase of the costs;
- domes: on the basis of the indication of the simulator, as shown in the graph of figure 22, we have opted for two domes with a 160,000 t capacity each, for a total 320,000 t capacity, that is about 20,000 t more than the maximum filling peak recorded in the twenty years the power plant has been in operation.

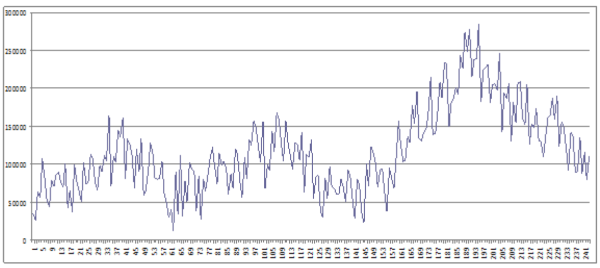


Fig.22

The maximum peak shown in the graph of figure 22 refers to a series of unfavourable circumstances identified by the model. For instance it is sufficient that two large ships arrive simultaneously over the week-end (when the grab cranes are not working) to cause, when the harbour opens up again, an excess of unloaded quantity compared to the daily coal consumption of the power station, thus creating an accumulation in the deposits.

The additional investments produce on the other hand, a net decrease in the demurrage costs which go from about 650,000€ to about 42,000€, and therefore the operating costs, notwithstanding the strong increase in the investment costs, increase by only 1,100,000 €/year.

As far as the occupation rates of the two berths are concerned, they prove to be very low, as it can be gathered from Table XII; such result was to be expected, since compared to the previous scenario, in which on the other hand a modest rate resulted, the average number of arriving ships has not changed, but the service capacity of the harbour has increased following the introduction of an additional berth.

	Dock 1		
Ship	Average dock staying time	number of ships	Total time
Handymax	2,09 d	6	12,52 d
Panamax	3,96 d	12	47,55 d
Capesize	4,84 d	16	77,45 d
		Total time:	137,53 d
		Simulation lenght:	365,00 d
		Dock 1 utilization index:	37,68%

	Dock 2		
Ship	Average dock staying time	number of ships	Total time
Handymax	1,94 d	3	5,81 d
Panamax	4,71 d	6	28,27 d
Capesize	5,43 d	5	27,13 d
		Total time:	61,21 d
		Simulation lenght:	365,00 d
		Dock 2 utilization index:	16,77%

Table XII

For the same reason, also the waiting time of the ships and the average number of ships waiting to be served have decreased, which in this configuration fall to the values shown in Table XIII.

Ship	Number of ships in the 20th year	Numbero of waiting ships	% of waiting ships on total ships	Average waiting time
Handymax	9	2	22,22%	0,96 d
Panamax	18	0	0,00%	0,00 d
Capesize	21	0	0,00%	0,00 d
Total	**48**	**2**	**4,17%**	**0,32 d**

Table XIII

The choice of the optimum configuration

In view of the results obtained, comparing the operating costs of the two identified configurations (the best one for the scenario with 1 berth vs. the one for the scenario with 2 berths), it has been decided to opt for the solution that requires only one berth, 2 grab cranes (with a 1,900 t/h free-digging rate each) and a ships mix with a prevalence of large ships. As far as the sizing of the domes instead, two domes are envisaged, with a 110,000 t capacity each.

IV. Robustness Analysis

In order to verify the robustness of the solution identified in relation to possible increases in the demand, we have increased the coal needs of the power plant to 4,000,000 t/year (+30%), 5,000,000 t/year (+60%) and 6,000,000 t/year (+100%).

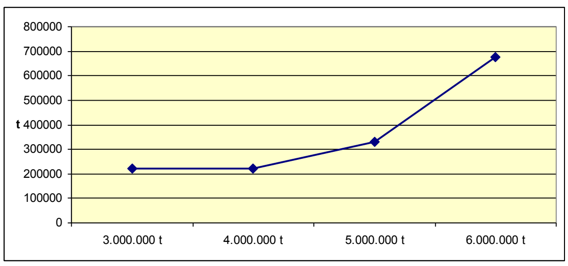


Fig.23

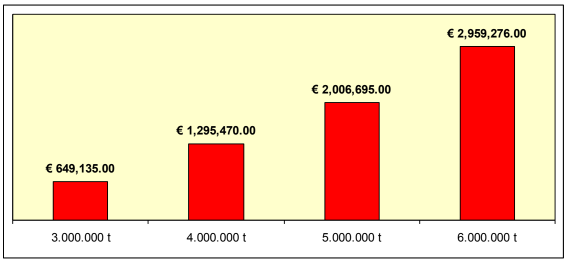


Fig.24

The analysis has shown again that the critical factor is the storage capacity since the utilization factor of the grab cranes and of the berths reaches, respectively, 15% and 37%.

The 220,000 t foreseen for the 3,000,000 t/year configuration would cover instead a maximum increase of the needs by 30%; furthermore it would be necessary to widen the dimensions of the storage area as shown in Figure 23.

The average demurrage in correspondence of each scenario would take on instead the values shown in Figure 24.

V. Conclusion

Thanks to the use of simulation and Response Surface Methodology techniques it was possible to identify problems and critical situations, which, if neglected or not duly considered, would have caused system malfunctions and hence higher operating costs. It was also possible to test the robustness of the solution chosen in the presence of possible changes in the power plant's demand due to possible expansions.

References:

[1] Mosca R., Meschinelli E., "Studio per il dimensionamento-investimento di un impianto in una azienda medio piccolo mediante l'uso della R.O.", Impianti, Franco Angeli Editore, No.3, 1975, pp 59-63.

[2] Mosca R., Giribone P., "A mathematical method for evaluating the importance of the input variables in simulation experiments", Proceedings of IASTED "Modelling, Identification and Control", Davos (CH), 1982, pp. 54-58.

[3] Mosca R., Giribone P., "Optimal lenght in O.R. simulation experiments of large scale production system", Proceedings of IASTED "Modelling, Identification and Control", Davos (CH), 1982, pp. 78-82.

[4] Angela di Febbraro, Alessandro Grua, Sistemi ad eventi discreti, McGrawHill, 2001.

[5] Averill M. Law, W. David Kelton, Simulation Modeling and Analysis, McGrawHill, 2000.

[6] Raymond H. Myers, Douglas C. Montgomery, Response Surface Methodology, Process and Product Optimization Using Designed Experiments, Wiley-Interscience, 1995.

[7] Evon M. O. Abu-Taieh, Asim Abdel Rahman El Sheikh, Discrete Event Simulation Environments, Information Science Reference, 2010.

[8] Douglas C. Montgomery, Design and Analysis of Experiments, Wiley, 2005.

[9] George E. P. Box, William G. Hunter, J. Stuart Hunter, Statistics for Experimenters, An introduction to Design, Data Analysis and Model Building, Wiley-Interscience, 1978.

[10] Norman R. Droper, Harry Smith, Applied Regression Analysis, Wiley-Interscience, 1998.

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Since '90 he works on combined utilization of simulation and AI techniques and on the applicability conditions and statistical reliability of special DOE techniques to simulation problems involving an elevated number of independent variables. He is member of important papers Scientific Committee (Int. Journal of Modelling & Simulation, Impiantistica Italiana, Production Planning and Control) and National and International Congresses (ANIMP-IASTED-ESS-etc). Member of ANIMP-SCS-AIRO-PM-AIIG. Titular in '98 of FESR funds about 1 billion ITL for 3 applied research projects. He increased the industrial research contract amount as DIPE Director from 250,000 USD/year in 1998 to over 1 million dollar/year in 2011 working with major international/national companies and agencies (Marconi, Elsag, COOP, NATO, Italian Navy, Fincantieri, PSTL etc.)

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