Analysis of river/sea transportation of iron ore bulk in Douro River

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ABSTRACT: This work presents a feasibility study and analysis of the transport of iron-ore by river-sea bulk carriers from a river terminal in river Douro to a sea terminal in Aveiro. The transport problem is divided in two parts. First the preliminary ship design in order to obtain the river-sea bulk carrier main dimensions, cargo capacity, power requirements and design speed. This is made by the means of non-linear optimization considering the route limitation and using a ship synthesis model. The second part is the analysis of the entire transport system (terminals, ship and route). This is made by means of simulation considering several scenarios with different terminal configurations and cargo equipment. The scenarios are compared by performance measures such as: annual cargo throughput, port time, waiting times, berth times and rate of equipment utilization in the terminals. With these results it's possible to identify the parameters that can benefit these transport system, making this simulation model an excellent tool for analyzing this transport problem or others of the same kind.

Keywords: Preliminary ship design, ship synthesis model, inland waterways, optimization, river-sea bulk carrier, discrete event simulation, bulk terminal design

1 INTRODUCTION

Over the last few years the Portuguese Government has been negotiating the exploitation of iron ore deposits located in Torre de Moncorvo, a sub-region of Douro. One of the issues relating to the operation of the mine is the transportation of the ore from the mine near location to export port, in this case, Aveiro or Leixões. Some of the transportation options that can be considered for this matter are: the fluvial-maritime transport, rail or transport through a pipeline. However, this work will address on the first option, the fluvial-ocean transportation.

Despite being one of the oldest modes of transportation and be highly dependent on environmental conditions such as the depth and width of the navigation route, currents, variations of the water levels, etc. inland waterway navigation together with contemporary technology allows seamless integration of the this mode of transportation with any other else, inclusive with the long-distance navigation, making it very competitive mode of transportation.

According to the Economic Commission for Europe-Inland Transport Committee (ITC) the main advantages associated with this mode of transport are: the cost-efficiency, lower power consumption propulsion, safety, environmental efficiency and less use of land (roads, rails, etc.). However, there are also disadvantages such as the previously mentioned geographical limitations and the influence of hydrological factors, such as floods or currents (UNECE - ITC 1996).

In the case of the river Douro its navigability is a reality, however the use of their potentialities, as a way of transportation, is far from being reached. The navigation channel is a waterway with about 200 miles long with minimum widths ranging between 40 and 60 meters and a minimum depth between 2.50 and 4.20 meters. There is a difference in level between the sea and the upper river, Barca d'Alva zone (border with Spain), which is won through five locks, all with similar features. For hydrological reasons the channel is not navigable throughout the all year (due to constraints imposed by the flood regime and river flow increase). The navigation schedule (IND 1998), is also conditioned, since the vessels can navigate only during the daytime.

By selecting this transport solution is necessary to consider all these conditions which are imposed and are inherent in this navigation channel. It's also necessary to consider the existing river traffic, namely the cruise ships and other leisure navigation activities, because these are the ones that use more actively this inland waterway.

2 ROUTE CHARACTERISTICS

The river route considered in this study extends between the new river terminal, near the Pocinho lock, and the mouth of the river, making a total of 95 miles, approximately. Along this route there are 4 locks which divide the river in several sections. All locks have identical characteristics, 12.10 m of width and length between 86.00 m to 92.00 m. A vessel with 83.00 m of overall length its able to pass through all locks (IPTM 2013).

The river has a minimum width of 40 m in bedrock and 60 m in alluvial bed. The minimum depth is 4.20 m, between the sea entrance and Pinhão (located between Régua and Valeira) and 2.50 m from there to Pocinho lock. Along the river there are several bridges which limit the air draft to a maximum of 7 meters.

Another type of restriction is the navigability of the waterway which is not possible during 38 days per year in average due to hydrologic reasons.

3 DRY BULK TERMINALS

3.1 Terminal Design Assumptions

In this study two terminals are under consideration: the new river terminal and the sea terminal. The river terminal is an export terminal, while the sea terminal is characterized by a transshipment activity, unloading the river-sea vessels and loading the larger ocean ships. These aspects influence both the type of cargo handling equipment and the storage areas needed. The following assumptions were made:

3.1.1 *Cargo handling*

The terminals will be assumed to be equipped with cranes provided with grab systems, which is the most common system for unload iron-ore according to (UNCTAD 1985) and with continuous ship-loaders. Both of these handling systems will travel in rails located along the quay. The load and unload capacities and the number of available handling systems will be subject to variations according to each simulation scenario.

3.1.2 *Storage*

Iron-ore is normally stored in open stockyards in long piles separated by gaps necessary for the conveyor belts and the rails of the stacking and reclaiming systems.

For storage calculations this study assumes that the stockpiles have a constant width of 20 meters and that they are filled to the maximum possible height. The iron-ore has the following characteristics: stowage factor 0.4 m^3/ton and repose angle of 40º (Ligteringen & Velsink 2012). The length of the piles can vary but it is always considered a 15 meters gap between stockpiles.

The stackers and reclaimers capacities will be considered such, so that the performance of the ship-loader or ship-unloader is not affected.

3.1.3 *Quay length*

The quay length is also a parameter to be defined in the terminal design. In this study it it's used a formulation given by (Kleinheerenbrink 2012):

$$L_q = 1.1 \times n_{berth} \times (\bar{L}_{vessel} + 15) + 15 \qquad (1)$$

where L_q is the quay length, n_{berth} is the number of berths and L_{vessel} the average of the length of the ships that visit the terminal. The 1.1 factor is used as a safety margin to ensure that no additional waiting time occurs (UNCTAD 1985).

3.1.4 *Turning basin*

The turning basin, the space necessary to maneuver the ship in and out of the terminal, will have a diameter of two times the overall length of the ship (Memos 2000).

3.2 River Terminal

In this study the river terminal doesn't exists yet so a possible location is proposed. This location was selected according to (Peixeiro 2012), where it is suggested that the future terminal should be located at the right side of the river downstream of the Pocinho lock.

The land selected has a total of 140,000 m^2 and the river makes a natural turning basin, just upstream of the proposed location that makes possible the maneuver of the river-sea bulk carriers.

The quay length as the number of ship-loaders will be a variable in each simulation scenario.

3.3 Sea Terminal

Contrarily to the river terminal, the sea bulk terminal in Aveiro already exists. According to this port administration (APA 2008) the bulk terminal has a quay length of 450 m and a total of 151,000 m^2 area for storage with the possibility of 67,000 m^2 for expansion.

The entrance in the Aveiro port is limited to vessels with less than 160 m of overall length and 9 m draught.

The currently existing terminal doesn't have the equipment and infrastructures appropriated to this transport problem and so an upgrade of its configuration would be proposed. This terminal has to have a berth designed for the loading operations of the Handy size vessel and other berths for the unloading of the river-sea bulk carriers.

4 SHIP SYNTHESIS MODEL

The concept of Ship Synthesis Model (SSM) dates back from the 70's (Reed, 1976). This tool determines whether a particular design is feasible and in that process makes changes to various characteristics of the ship to arrive at a balanced design.

The SSM is the sequence of numeric methods that is used to integrate a number of different aspects of the ship design. In the initial ship design stage, many of used methods are empirical and rely on formulas obtained from regression analysis of data from databases of similar ships or semi-empirical and rely on statistics from systematic studies.

4.1 Hull Form and Compartment Layout

Because 75% of the route is in inland waterways, without waves, the hull form adopted has a very high block coefficient (Cb) value. The hull form should be simplified with the extended use of developable surface for lower building cost and with no bulb (Figure 1).

The common arrangement of the cargo area of sea-going bulk-carriers is the single hull with hopper and wing tanks. Typically, bulk carriers for inland navigation adopt a different configuration, double-skin, which allow them to have a more multi-purpose type of usage, with box shaped cargo hold(s) also appropriate for carrying containers and other unitized types of cargo.

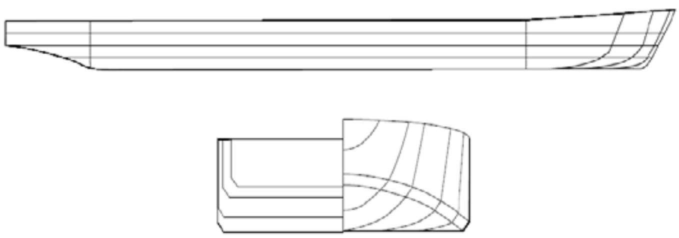

Figure 1: Lines and Body Plan of a possible hull form

The estimate of the cargo capacity can be done based on the configuration of the midship section and on the length of the cargo area. The latter depends from the lengths of the aft peak, engine room and fore peak tank. SOLAS Chapter II-1 specifies the location of the collision (IMO, 2012a). However, SOLAS is not mandatory for ships designed for domestic voyages but taking into consideration that in this case 75% of the voyage is done in inland waterways, it was assumed to consider a less conservative position of the collision bulkhead, adopting the 0.04L value recommended by the European Directive 2006/87 (EC, 2006).

The length of the engine room is estimated as a function of the propulsion system and of the propulsive power installed. The location of the aft engine room bulkhead is assumed at 0.04L.

4.2 Freeboard

The International Convention on Load Lines (ICLL) is adopted, in compliance with the flag authorities' criteria.

4.3 Lightship Weight

The lightship weight is estimated as the sum of three main components: structures, machinery and outfitting. The structures are composed by the hull and the superstructure.

The results from the empirical expressions were validated taking into consideration data from similar existing ships and also from a recent works focused on inland navigation vessels (Hekkenberg, 2013; Michalski, 2005).

4.4 Hull Resistance

The hull resistance is estimated with the Holtrop & Mennen method (Holtrop & Mennen, 1982; Holtrop & Mennen, 1984). Although this method is based on data from larger ships it is also very commonly adopted as a reference for ships with smaller dimensions and even for inland navigation vessels.

The ship resistance and maneuverability depend on the depth of the navigation area. The effect of depth can be noticed in medium deep water, is significant in shallow water and dominant in very shallow water. In the present case the values of (h/T) range from 1.60 to 1.13, with a maximum water depth of 4.20 m. In this depth conditions, three effects must be taken into consideration in addition to the bare hull resistance: the added resistance due to shallow water, the added resistance due to restricted channels and the squat.

Shallow water increases friction resistance, and this added resistance is especially noticeable near the critical depth Froude number F_{nh}=1.0 (Bertram, 2012).

If the ship sails in restricted width, this resistance is further increased. An important factor for this effect is the blockage factor, *S*, defined by

$$S = \frac{A_S}{A_C} \tag{2}$$

in which A_S is the cross-section area of the ship's underwater part of the hull and A_C is the section area of the waterway.

The method adopted to estimate the speed loss due to shallow water effect (Lackenby, 1963) although producing over estimated values in some situations (Raven, 2012), is widely used and recommended by ITTC (2005) and is being considered for the revision of ISO 15016 Standard methodology for EEDI verification procedure. In the voyage model, the speed loss is converted into additional resistance.

$$\frac{\Delta V}{V} = 0.1242\left(\frac{A_S}{A_C} - 0.05\right) + 1.0 - \left(tanh\left(\frac{1}{F_{nh}^2}\right)\right)^{0.5} \tag{3}$$

Ships with a displacement hull navigating at even moderate speed in low depth waterways are subject to a phenomenon of increasing sinkage and trim, designated by squat (Barrass, 1979). This effect is due to a pressure drop under the hull resulting from the flow confinement and asymmetry of motion.

In this model, the bow squat was estimated in accordance with the Eryzlu formula (Eryzlu & al, 1994) as adopted by the Canadian Coast Guard (CWNMG, 1999) and applied in the St. Lawrence Seaway:

$$S_b = a\frac{h}{T}(F_{nh})^b\left(\frac{h}{T}\right)^c K_b \tag{4}$$

S_b is the bow squat, the constants are $a = 0.298$, $b = 2.289$, $c = -2.972$. The coefficient K_b depends from the ratio width of the waterway and the breadth of the ship and is obtained by the expressions

$$K_b = \frac{3.1}{\sqrt{\frac{W}{B}}} \quad \text{if } W < 9.61B$$
$$K_b = 1.0 \quad \text{otherwise} \tag{5}$$

4.5 Propulsion System

The issues of the ship emissions in an environmental sensitive area and the current fuel prices are the motivation for the analysis of two propulsion system alternatives: a conventional solution based on a four-stroke Diesel engine running on Marine Diesel Oil (MDO) or a dual-fuel engine capable of using LNG.

In general, LNG is safer than Diesel and has lower emissions. The emissions of SO_x and particle matter (PM) are almost eliminated, the NO_x is reduced by about 90% and the CO_2 by 20 to 25%.

Although the ship speeds in cargo and in ballast conditions can be quite low, it was assumed that the installed propulsive machinery should be able to guarantee at least the minimum speed of 13 km/h (7 knots) which is a requirement of the Directive 2006/87 (EC, 2006) which is applied in the European inland waterways.

4.6 Ship Energy Efficiency and Emissions

The Energy Efficiency Design Index (EEDI) is a measure of the ship energy efficiency. Its determination is mandatory for all new ships built after 1st January 2013.

Although the requirements from IMO are not applicable to inland waterways, the fact remains that the expected large number of ships sailing in a vineyard region is an environmental concern. Therefore, the EEDI is checked and the total amount of CO_2 emissions is estimated in accordance to the IMO requirements (IMO, 2012b; IMO, 2012c).

4.7 Ship Building Cost and Operational Costs

The assessment of the ship design alternatives cannot be based exclusively on technical criteria, the economic aspects are essential for any engineering project. The shipbuilding cost is an obvious criterion, but some of the impacts from the design options made can only be evaluated on the long run. So, it was developed a model of the round-trip voyage, to support the estimate of the ship operational costs.

The initial ship cost is estimated by empirical formulas as the sum of three main components, the structures the machinery and the outfitting.

The results were compared with prices from existing ships and correction factors were introduced in the model. To make the exercise more realistic, the capital costs resulting from a bank loan to finance 70% of the ship investment were considered.

The price of the fuel used was based on the average of 2013 values (Fearnleys, 2013).

The price of LNG bunkers is typically specified with reference to its calorific value (US$/Million BTU). In order to simplify the comparisons with MDO, in this study, as approximation, it was assumed the LNG price to be 35% lower than bunker fuel 300 cst.

Regarding the running costs of the ship, it was adopted a common breakdown of the costs (Stopford, 2009).

5 VOYAGE MODEL

Freight transportation is the movement of goods between two locations. Many times, it involves several modes of transport and it is designated by multimodal. Additional transfer systems (transshipment) and temporary storage may be required when more than one type of transport is used, or when there is either the need to combine smaller parcels into large ones, or to split large amounts into smaller parcels.

A data model was developed to specify the classes of entities used in a marine transport problem, their attributes and associations. A *Voyage* is composed by one or more *Legs*. The *Leg* class can be associated to zero or more objects of the class *Ship*. In this context zero means that this leg is not a waterborne transport mode – it can be made by *Rail* or by *Road*, in multi-modal types of voyages. Waterborne legs (seagoing or inland) are associated to one or more *Ships* that can be of different characteristics for example in voyages with transshipment.

The *Leg* class objects are used to model voyage segments with some different characteristics, not necessarily between two ports. For example, a *Leg* can be used to specify a path through a *Lock* or a *Canal*.

Each *Leg* is also associated to one ship *ServiceCondition*, each characterized by a service speed and a load condition (*Fully_loaded*, *Ballast*, etc.).

The information associated to each *Leg* supports the determination of the time spent, the associated costs and also the ship emissions. The sum of all the *Legs* produces results for the complete *Voyage*.

The *Ship* class is associated to one or more objects of the type *PrimeMover*. The objects of this class can be of several types (*DieselEngine*, *GasTurbine*, *SteamTurbine*).

In this particular case study, the round-trip voyage was considered to be split into four legs. In Table 3 is presented the data associated to each leg.

In this case two service conditions were considered: fully loaded and ballast.

The river path is associated to a set of physical dimensions limitations enumerated in Table 1.

Table 1. Round trip legs and characteristics

Voyage Legs	Route Characteristics
1	Length: 95 nm River course Fresh Water Shallow water Ship Fully Loaded Locks
2	Length: 32 nm Coastal sea route Sea Water Deep sea Ship Fully Loaded
3	Length: 32 nm Coastal sea route Sea Water Deep sea Ballast
4	Length: 95 nm River course Fresh Water Shallow water Ballast Locks

For each leg, the ports visited (if any) were identified and characterized with specific data concerning loading/unloading rates, service fees and service time.

The voyage connects two terminals, a river loading terminal (non-existing) and a sea port unloading terminal.

Table 2. Assumed terminal characteristics

Terminal	River	Sea
Cargo handled	100%	100%
Cargo handling equip.	Ship loader	Cranes w/ grabs
Cargo handling rate [ton/h]	2,000	500
Cargo handling costs [$/ton]	0.0886	
Terminal fees [$]	0.1961xGT+0.1989xCWT	
Service time [h]	0.5	1.0

In Table 2 are summarized the terminal characteristics assumed in this study.

6 DESIGN OPTIMIZATION

6.1 Model Validation

Due to the generic and empirical nature of many of the methods used in the SSM, the model must be validated and eventually calibrated before starting the optimization process. This validation is done by comparing the values obtained from the model with real data from similar existing vessels.

There is not many information available concerning ship lightweight. In this study some data was gathered regarding existing ships (Egorov, 2014), (Egorov, 2007). However these ships are all ice class with strengthened hulls which implies an addiction in the lightweight due to structural reinforcements.

In order to do a reasonable comparison between the model results and the existing ship data, the extra weight due to ice class has to be deducted. It was considered that for the case of these vessels (LU1 and LU2 Russian Maritime Register of Shipping ice classes) the ice class reinforcement represents 1% increase in the ship lightweight (Dvlorak, 2009).

The first lightweight values given by the model were slightly deviated from the real data. A correction factor was then applied to the model estimation.

To validate the cargo capacity estimation method the actual cargo volume was computed in a 3D model developed according to the hull form presented in Figure 1. This comparison revealed that the model was overestimating the volume capacity by approximately 6%. The estimation formula was improved to better match this result.

6.2 Optimization

The optimization procedure was carried out with the following configuration: one objective, six design variables and sixteen constraints.

It is common knowledge that engineering problems are in their essence multi-objective. However, at a higher level of decision, and in order to downsize the problem to acceptable computation times, many objectives can be replaced by suitable constraints. In this case, it was adopted a single objective, the minimization of the Required Freight Rate (RFR). The design variables considered are the ship's Lpp, Depth, Draught, Cb, and the service speeds, both in loaded and in ballast conditions.

Regarding the constraints, two main types were taken into consideration: physical limitations and technical requirements. The physical limitations result from the waterway configuration (maximum depth and width), lock sizes (maximum length overall and breadth) and air draft (existing bridges). Regarding the technical constraints, they are related with the freeboard, the EEDI, the cargo volume and the clearance under keel. The stability was not considered an issue due to the nature of the cargo and the type of route, mainly in calm water.

The under keel clearance (UKC) of the ship is obtained by the expression

$$UKC = h - T - d - s \qquad (6)$$

in which h – water depth, T – ship draught, d – ship trim, s – squat, all in meters.

The minimum UKC value acceptable depends from the local morphology of the bottom, but 0.50 m is a commonly adopted value. Although the river has some regions with a depth limitation of 4.20 m, the extent of the limited lengths does not justify the use of the UKC has a design constraint.

The design constraints are summarized in the Table **6**.

Table 3. Optimization constraints

Loa	<= 83.00 m
Draught	<= 3.70 m
Depth - Draught	>= Summer freeboard IMO
Cargo volume	>= CDW/Cargo Dens.
Attained EEDI	<= Reference EEDI

The optimization is carried out by an efficient non-linear algorithm, GRG2 (Lasdon & al, 1978). To deal with the local behavior of this algorithm, 100 starting points are randomly generated in the design space and for this purpose, lower and upper limit values were defined for each design variable.

The SSM, the voyage model and the optimization procedure were carried out in a software tool (Ventura, 2013), that was extended to cope with inland and seagoing ships and voyages.

The SSM was first run to determine the propulsive power needed to attain the minimum service speed of 7', in fully loaded condition. The resulting power was used to select the engine. To be noted that from the required service and ballast speeds an engine with lower power can be selected.

6.3 Optimization scenarios

Two scenarios were considered: on the first, the ship has a four-stroke Diesel engine burning MDO; in the second, the engine burns LNG.

It is considered that the storage of the LNG is made in an open deck. This type of storage only has to oblige to a distance at least B/5 from ship's side but not less than 760 mm (IMO, 2009). This solution doesn't imply any alteration in the SSM, the compartment layout can continue to be made in the same way (see Section 4.1) and the LNG storage is placed in the open deck. It was also considered that the storage is made in containerized tank systems, which are a modularized and flexible solution. The LNG fuel tank containers can be transported and refilled in land, thus eliminating the requirement of a LNG bunkering facility nearby.

For the economic evaluation it was assumed that the LNG engine alternative represents a machinery cost 20% higher.

6.4 Results

The main characteristics of the resulting ship are similar to both alternatives and summarized in the Table 4.

The main differences between the two propulsion options are reflected in the economical side. The LNG is cheaper and the specific consumption of the engine is lower when compared with the MDO version. These two facts are perceptible in the voyage costs, namely in the fuel costs which represent 54% of the voyage cost for the MDO alternative, while only 28% for the LNG.

Table 4. Characteristics of optimum ship

		MDO	LNG
Loa	[m]	83.00	
Lpp	[m]	80.50	
Breadth	[m]	11.00	
Depth	[m]	4.76	
Draught	[m]	3.70	
Cb	[--]	0.85	
Deadweight	[ton]	1,910	
Cargo Deadweight	[ton]	1,711	1,775
Service speed (loaded)	[knots]	10.59	10.04
Service speed (ballast)	[knots]	9.41	10.16
RFR	[$/ton]	5.644	4.705
EEDI	[g CO2/t/nm]	26.183	21.086
CO2 emissions	[t/year]	1,847	1,238
CO2 reduction	[%]	-	33%

Based on the RFRs obtained it's possible to calculate the time needed to recover the extra investment (payback time) of the LNG alternative. The payback time is obtained by the expression

$$t_{payback} = \frac{\Delta Investment_{LNG,MDO}}{Q_{annual} \times \Delta RFR_{LNG,MDO}} \quad (7)$$

in which $t_{payback}$ – time to recover the investment in years, $\Delta Investment$ – the additional investment, Q_{annual} – annual cargo in tons/year , ΔRFR – the RFR difference in $/ton.

According to the model results and the expression (7) the $t_{payback}$ for the LNG extra investment is actually less than one year ($t_{payback} \sim 0.62$ years).

Another parameter that differentiates one propulsion alternative from the other is the EEDI. Like it was explained before, the IMO rules regarding the emissions are not applicable to inland waterways but since these vessels will be sailing in environmental sensitive areas (vineyards, touristic sites, protected landscape areas, etc.) the emissions should be minimized. Both alternatives are complying with the IMO values but the emissions for the MDO engine are higher. In fact, in comparison, the LNG system shows a 33% reduction in the CO2 year emissions. Considering that this iron ore supply chain will be operated by a considerable fleet of ships (7 to 8 ships, if we considered an annual production of 3 Million tons of iron ore) the LNG represent a total reduction of approximately 4,800 tons of CO2.

7 TRANSPORT SIMULATION MODEL

This model covers the entire transport system (terminal operations, locks, existing traffic, etc.) from the arrival of the iron ore to the river terminal until its exportation from the sea terminal. These two points are the boundaries of this study.

7.1 River operation

7.1.1 *Iron-ore arrival*

The arrival of iron-ore is modeled by a *Poisson* distribution. This kind of distribution is commonly used for modeling the times at which arrivals enter a system (Gallager 2014). It's assumed that the iron-ore arrives already processed in the form of pellets.

7.1.2 *Loading*

In a real scenario the loading operations on the terminals are always subjected to delays which can be caused by human factors, climatic factors, etc. This uncertainty on the loading time has to be considered on the simulation model and it was modelled by a Gamma distribution as proposed in (Assumma & Vitetta 2006). The loading time can therefore be obtained by the expression:

$$T = T_{det} + T_{stoc} \quad (2)$$

were T is the total loading time (or service time), T_{der} is the deterministic loading time under normal conditions and T_{stoc} is the stochastic time calculated under unexpected conditions (e.g delay, breakdown, etc.) represented by a Gamma distribution.

T_{det} is calculated considering only 70% of the ship-loader rated capacity, a conservative estimate based on (UNCTAD 1985).

7.1.3 *Berthing and deberthing operation*

According to (UNCTAD 1985) these two operations, together, have a duration of about 2 hours. Since the river-sea vessels are relatively small vessels with good maneuverability, in this model it is assumed that these operations will take only 1 hour.

The berth(s) and the cargo handling system(s) will be considered as resources which are occupied by the vessel during the total service time. These resources have a capacity which depends on the configuration of the terminal, i.e. if the terminal has two berths than the "resource berth" has capacity to handle two vessels at the same time.

7.1.4 *River route*

As it was already mentioned in Section 2 the total river route from the terminal location to the sea entrance has a total of 176 km (approximately 95 miles) including 4 locks.

The locks are modeled as a resource which can only be used by one vessel at time. The service policy used in the locks is "First-come, First-served" (FCFS). In this study it was not possible to gather much information about the lock operation time behavior. For this reason was considered that this process has a low time variability and can be represented by a normal distribution with an average of 45 minutes (Mota 2012) and +/- 5minutes of standard deviation.

7.1.5 *Existing traffic*

It is vitally important to consider the existing inland traffic because it shares the same waterway and locks.

Representing the total waterway traffic would be impossible so in this model there are only represented the cruise vessels, an activity that represents the majority of the traffic. A total of 10 different cruise vessel routes were considered. The different schedules and seasonality of these routes are also implemented into the simulation model, in accordance with the published information.

7.2 Sea operation

The route between the Douro sea entrance and the sea terminal has a total of 32 miles (see Section 2). In this leg of the route it is considered that the river-sea vessel can sail at any speed.

7.2.1 *Port entrance*

According to the port authorities, every vessel is obliged to have a port pilot during the entrance and berthing operation. In the case of a vessel with more than 95 meters the utilization of tugboats is also mandatory. Both of these requirements are included in the simulation model.

7.2.2 *Loading/Unloading operation*

Both the loading and the unloading operations will be represented using the method described in Section 5.1. In the case of the unloading operation the time under normal conditions will be calculated considering only 50% of the ship-unloader rated capacity (UNCTAD 1985).

The berthing and deberthing operations will be considered with the same characteristics as in the river terminal. The berth and handling systems will be considered as resources as in the case of the river terminal. Regarding the handysize vessel this will have its own berth, dedicated to the loading of the vessels. The berthing and deberthing operations will have an assumed duration of 2 hours for the handysize vessels.

The sea terminal operation is represented in Figure 2.

7.2.3 *Handysize vessel*

This class of ship represents the maximum size that can enter in the Aveiro port due to its physical restrictions (see Section 3.3).

The size of the handysize vessel is generated with a certain variation represented by a Normal distribution with an average of 16,150 DWT and a standard deviation of 3,650 (Stopford 2009).

It is considered that the handysize vessel will always be fully loaded in this terminal, i.e. if there is no iron-ore available in storage to fill the entire cargo capacity of the handysize vessel, the ship will have to wait.

8 SIMULATION

The simulation and the previously described model were developed with discrete event simulation software system (Rockwell Automation 2010).

8.1 Model verification and validation

Model verification is an important step in simulation modeling. It is applied to ensure that the model is running properly or not. The verification of this model was made in several steps:

- Conducting model code reviews;
- Checking if the outputs were reasonable;
- Watching the animation for correct behavior.

In this simulation, each part (River terminal, voyage between terminals and Sea terminal) was run separately to check if it responds properly to different input variations.

The objective of validation is to demonstrate that the model is a reasonable representation of the real system. Since this transport system doesn't exit, there is no real life data with which compare the model results and due to this the model couldn't be validated.

8.2 Simulation assumptions

It is assumed that the river channel is dredged to ensure a depth of 4.20 meters between the location of the river terminal and the sea entrance.

Due to the navigation restrictions pointed in Section 2, a year of simulation has a total duration of 327 days. The results presented in this section are the average values of a 5 year simulation.

Regarding the terminals working schedule it's assumed that both terminals can work 24 hours per day, 7 days per week.

Currently the navigation in the river is restricted to daytime only. There were made several runs to see how the navigation schedule restriction affects the model. For a river navigation schedule from 7am to 20pm each vessel is "forced" to be idle an average of 9 hours in each round voyage, which is more than half of the time needed to do a voyage from the river terminal do the sea terminal, and vice-versa, without a navigation schedule restriction .This implies a large impact in the transport chain and due to this fact it is assumed that the river navigation schedule doesn't have any restrictions, has it is proposed in (Peixeiro 2012).

8.3 Performance indicators

The scenarios will be evaluated according to the following operational Port Performance Indicators (PPI's) as defined in (Kakderi & Pitilakis 2011):

- Port time: Total time spent by a ship since it's entry till it's departure (this PPI is also known as Turnaround time, TAT);
- Average waiting time for berth: the average time a vessel remains idle waiting for berthing;
- Berth time: average time the vessel is berthed (berthing and deberthing operations included);
- Service time: average time spent between berthing and deberthing;
- Tons per ship-hour in port: total tonnage worked, divided by the total time between arrival and departure;
- Berth occupancy factor (BOF): the time that a berth is utilized, divided by the total time;
- Storage occupancy: average and maximum storage occupancy.

In addition to these PPI's the simulation model also provides other performance indicators like:

- Locks occupancy and average waiting time;
- Fleet utilization: average number of vessels utilized.

8.4 Simulation scenarios

A total of seven scenarios were created. In six of them it's considered an iron ore production of approximately 3 million tons per year, which is the estimated mine annual production according to (Público 2012).

Table 5: Simulation Scenarios

		Pocinho river terminal			Aveiro sea terminal			Handysize vessel
Scenario	No. of ships in the fleet	No. of berths	Handlers per Berth	Loader capacity [t/h]	No. of berths	Handlers per Berth	Unloader capacity [t/h]	Time between arrivals [days]
1	10	1	1	2,000	1	1	1,000	2
2	10	1	1	2,000	2	1	500	2
3	10	1	1	2,000	2	1	1,000	2
4	10	2	1	1,000	1	1	1,000	2
5	10	2	1	2,000	1	1	1,000	2
6	10	2	1 handler for 2 berths	2,000	2	1 handler for 2 berths	1,000	2
7	22	2	1	2,000	2	1	1,000	2*

*Considering Handymax vessels

In the seventh scenario it is evaluated the scalability of the solution in a condition in which the mine annual production increases to approximately 6 million tons per year.All the scenarios are summarized in Table 5.

8.5 Result analysis

In Figure 4 are represented the average port time for each scenario, the average waiting time for berth, the tons per ship hour in port and the berth occupancy factor.

Scenario 1 can be seen as the “basic” scenario, using only one berth and one cargo handler in each terminal. The unloading operation is more time consuming than the loading operation due to the lower capacity of the unloader compared with the capacity of the ship loader in the river terminal. This fact has an impact in the port time, in the tons per ship hour in port and in the average waiting time.

If one more berth and one more handler are added to the sea terminal, but the handler’s capacity is reduced (scenario 2) the port time in the sea terminal increases and the tons per ship hour in port decrease. The main advantage of this new terminal configuration is the reduction of the average waiting time for berth, but by lowering the cargo handler capacity the unloading operation becomes more time consuming that in scenario 1 giving a higher port time that in the previous configuration despite of the reduction in the average waiting time for berth. By other end if the cargo handler capacity remains the same as in the scenario 1, which corresponds to the configuration tested in scenario 3, the PPI’s port time , tons per ship hour in port and average waiting time demonstrate a good improvement in the sea terminal performance.

Following the same kind of analysis regarding the river terminal, which correspond to the scenarios 4 and 5 the same kind of conclusions can be drawn.

If instead of adding a combination of one berth and one handler in each terminal we only add a berth (scenario 6) the results obtained reveal that in terms of port time a small decrease is noticed when comparing to the configuration in scenario 1 and an increase if we compare with the configuration two berths and two handlers (scenario 3 and 5), revealing that this configuration reacts as a middle ground between the previous configurations. The same can be concluded for the PPI tons per ship hour in port.

The average waiting time for berth also decreases with the configuration presented in scenario 6

8.5.1 *Berth occupancy factor*

For scenario 1 the berth occupancy in the river terminal it’s above these recommended values (Memos 2000, UNCTAD 1976), this indicates a sign of congestion as can be seen in the average waiting time for berth.

By adding one more berth the occupancy decreases to a factor slightly lower than the recommended one and the waiting time for berth is also reduced relieving the congestion in the terminal. The same can be said for the river terminal. However for scenarios 3 and 5 the occupancy factor becomes significantly low which can indicate an oversized terminal design for both sea and river terminals.

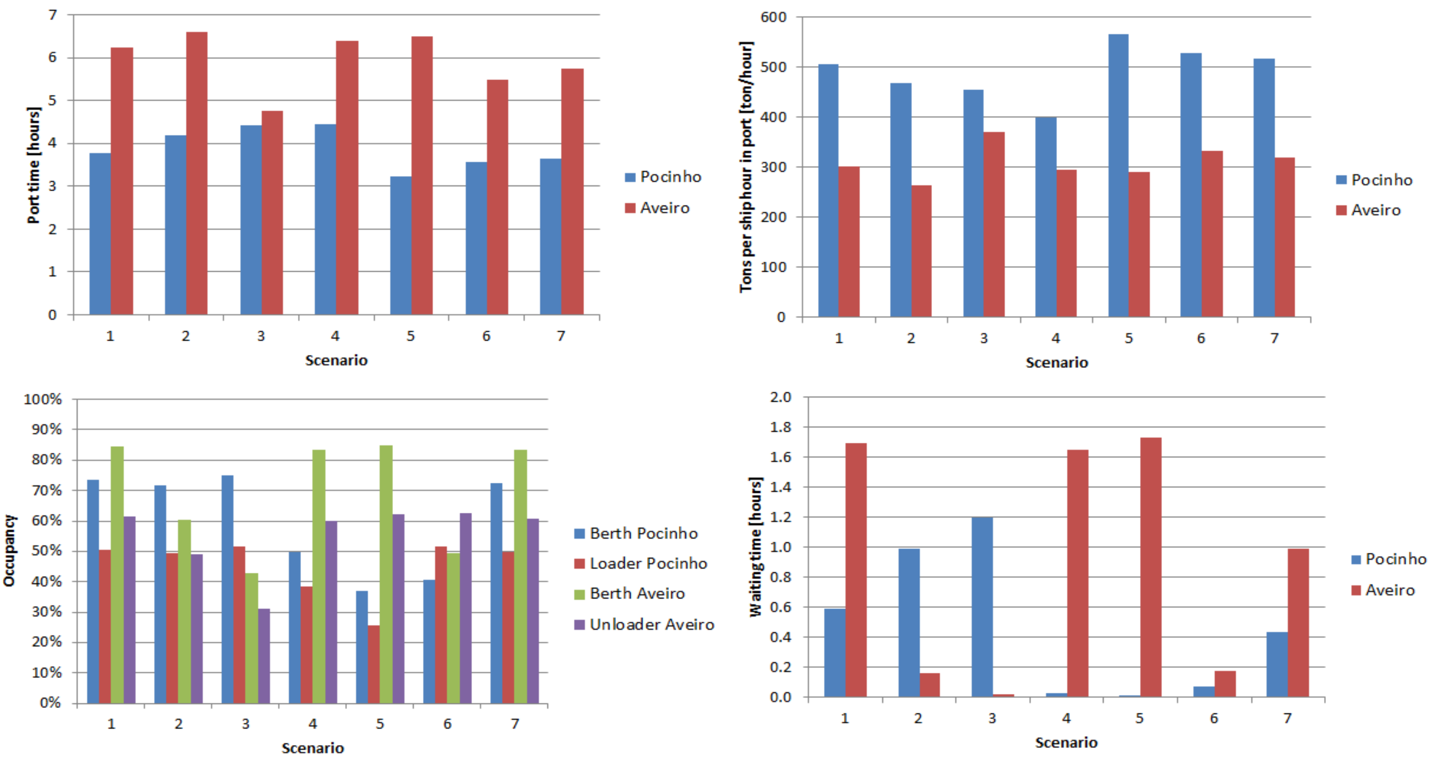

Figure 2: From top to left - Port time; Tons per ship hour in port; Berth occupancy; Average waiting time for berth

The berth occupancy factor in scenario 6 is in a good range of values when compared with the recommended ones. In this case it's important to notice that the cargo

8.5.2 *Berth occupancy factor*

For scenario 1 the berth occupancy in the river terminal it's above these recommended values (Memos 2000, UNCTAD 1976), this indicates a sign of congestion as can be seen in the average waiting time for berth.

By adding one more berth the occupancy decreases to a factor slightly lower than the recommended one and the waiting time for berth is also reduced relieving the congestion in the terminal. The same can be said for the river terminal. However for scenarios 3 and 5 the occupancy factor becomes significantly low which can indicate an oversized terminal design for both sea and river terminals.

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The berth occupancy factor in scenario 6 is in a good

range of values when compared with the recommended ones. In this case it's important to notice that the cargo handler's occupancy is slightly higher that the berth occupancy, this relates to the fact that exist only one handler for two berths. This fact also adds an additional waiting time when the vessel is already berthed but waiting for the availability of the cargo handler. This additional waiting time is contemplated in the PPI port time

8.5.4 *Storage occupancy*

The storage occupancy in the river terminal is very low (has a maximum of approximately 29%) which indicates that the iron ore flow from the mine matches the "transport flow" by the river-sea vessels. For the tested scenarios and for this simulation model it's possible to conclude that the area proposed for the river terminal in Section 3.2 can be reduced.

In the sea terminal the storage occupancy is slightly higher, achieving maximum values of 65%. However the average occupancy still is somehow low, which is an important fact because the sea terminal serves other ships and according to (IPTM 2012) the Aveiro terminal worked 780,000 tons of bulk cargo in the year 2012. For this reason it's important to leave a certain margin of not occupied storage area.

8.5.5 *Expansion scenario*

In scenario 7 an increase in the mine iron ore production was considered. To make the transportation of the 6 million tons of iron ore from Pocinho to Aveiro the time between arrivals of the the handysize vessels had to be reduced to 1 day otherwise the storage space will be full, generating a bottleneck in the transport system.

This time between arrivals seems to be not realistic because it will imply a big fleet of handysize vessels. A possible solution is to upgrade the Aveiro port characteristics to make possible the entrance of larger vessels, which according to the port administration will happen in the future changing the limitations to a maximum LOA of 200 meters and a draft of 11 meters. With these new limitations the entrance of handymax vessels will be possible and the time between arrivals can be 2 days for this scenario.

The results regarding scenario 7 presented in this study considered this new solution. The handymax DWTs are generated as in Section 4.3.3 but the normal with a different normal distribution (Stopford 2009).

8.5.6 *Lock utilization*

The locks along the river route are used not only by the river-sea vessels but by the already existing waterway. Considering the traffic with the characteristics in Section 4.2 this transport system represents a utilization increase of approximately 30%.

In scenario 7 due to the increase of the river-sea vessels fleet, from 11 to 22 vessels, the lock utilization increases drastically to approximately

80%. This will have an impact on the average waiting time in the locks. This can be understood as a sign of a possible future bottleneck in the transportation system. It is recall that scenario 7 considers an increase of the mine iron ore production to double.

9 CONCLUSIONS AND FUTURE WORK

The design of a river/sea ship to a specific transport problem was analyzed and a simulation model of the transportation system was developed.

Regarding the ship design the SSM and the optimization were run for two fuel/engine alternatives, a MDO version and a LNG version. The dimensions obtained for these two alternatives are essentially similar, even the operation speeds for the two loaded conditions are similar. However, the lower RFR and CO2 emissions, reflected in the EEDI values, are significantly different and in conjunction with the short payback period make the LNG alternative the best solution.

Regarding the simulation of the transport system the differences between all the performance indicators can be noticed and are somehow distinct through the different terminal configurations tested in this study; however the variations per se are not large. Nevertheless the performance differences between each terminal configuration are noticeable which makes possible to draw some conclusions from the operational point of view.

Considering all the made assumptions, simulation scenarios and the ship characteristics a fleet of 10 ships will be necessary to ensure the estimated annual iron ore production. The terminal configuration of 2 berths and only one cargo handler in each terminal appears to be the best option. This configuration is a good trade-off between the system performance and the number of used resources. Another advantage of this configuration is the capability to sustain a possible iron ore production increase just by adding one cargo handler in each terminal and by expanding the river-sea vessel fleet.

For future research in this subject it is recommended to include the economical assessment of both the ship and the terminals, namely the investment in bulk handling equipment. Another aspect that should be considered in the future is the actual river course morphology by locating the areas where the river is narrower or has lower depth. Multi-objective optimization algorithms should also be used to determine the results from additional objectives such as the maximization of the ship energy efficiency, by the minimization of the EEDI.

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