Maritime Technology and Engineering

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Editors:
C. Guedes Soares
T.A. Santos

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MARITIME TECHNOLOGY AND ENGINEERING

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Maritime Technology and Engineering

Editors

C. Guedes Soares

Centre for Marine Technology and Engineering (CENTEC), Instituto Superior Técnico, Universidade de Lisboa, Portugal

T.A. Santos

Ordem dos Engenheiros, Portugal

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Wind & wave modelling

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Preface

Since 1987, the Naval Architecture and Marine Engineering branch of the Portuguese Association of Engineers (Ordem dos Engenheiros) and the Centre for Marine Technology and Engineering (CENTEC) of the Instituto Superior Técnico (IST), Technical University of Lisbon, (now University of Lisbon) have been organizing national conferences on Naval Architecture and Marine Engineering. Initially, they were organised annually and later became biannual events.

These meetings had the objective of bringing together Portuguese professionals, giving them an opportunity to present and discuss the ongoing technical activities. The meetings have been typically attended by 150 to 200 participants and the number of papers presented at each meeting was in the order of 30 in the beginning and 50 at later events.

At the same time as the conferences have become more mature, the international contacts have also increased, and the industry became more international in such a way that the fact that the conference was in Portuguese started to hinder its further development with wider participation. Therefore, a decision was made to experiment with having also papers in English, mixed with the usual papers in Portuguese. This was first implemented in the First International Conference of Maritime Technology and Engineering (MARTECH 2011), which was organised in the year that Instituto Superior Técnico completed 100 years, and has included 90 papers.

In this Second International Conference of Maritime Technology and Engineering (MARTECH 2014), the papers received are only in English and have been compiled in the present book. More than 200 abstracts have been submitted and after a review process, a total of 150 papers have been accepted which constitutes a demonstration of the growing interest in this conference. The Scientific Committee had a major role in the review process of the papers although several other anonymous reviewers have also contributed and deserve our thanks for the detailed comments provided to the authors allowing them to improve their papers. The participation is coming from research and industry from almost every continent, which is also a demonstration of the wide geographical reach of the conference.

The contents of the present books are organized in the main subject areas corresponding to the sessions in the Conference and within each group the papers are listed by the alphabetic order of the authors.

We want to thank all contributors for their efforts and we hope that this Conference will be continued and improved in the future.

C. Guedes Soares & T.A. Santos

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The past, present and future of the ocean engineering activities

H. Maeda
Department of Oceanic Architecture and Engineering, College of Science and Technology, Nihon University, Japan

ABSTRACT: Ocean engineering activities are categorized into four fields, those are, the ocean field of resources, the ocean field of space utilization, the ocean field of crossing power, and the ocean field of experience, according to Boeckmann (1924). The past, present and future of those ocean engineering activities are surveyed and outlooked from the stand point of technology innovation, especially on floating platforms which include ships. In the past, there were two important industries such as fishery and ocean transportation such as shipping. In the present, ocean industries are very active in all four categorized ocean fields. Near future ocean activities may include ocean minerals, ocean renewable energy, countermeasures for global warming etc. They are almost realized, then, they depend on so called realization engineering or satisfying engineering. Far future ocean activities may include VLFS (Very Large Floating Structure), Mega-Float, floating ocean airport, floating ocean city etc. which depend on fantastic or romantic or illusion engineering. Ultra far future ocean activities may include "New Noah's Ark" or "Floating Ocean Great Wall" so called "Giga-Float" which depend on dream engineering. Ultra-Ultra far future, 500 million years later from now on, before the extinction of human being and biosphere on the Earth, the human being needs to evacuate from the Earth to a space colony, using floating ocean platform and space elevator. Then human being shall live forever. The human being always needs floating platform with contingency plan to continue to keep their selfish gene stable.

1 INTRODUCTION

Ocean engineering activities can be reflected in the corresponding industries. In the following, topics of ocean engineering activities are introduced along the time axis with the corresponding industries, from the stand point of the category of the ocean fields.

The time axis consists of the Past, the Present, the Near Future, the Far Future, the Ultra Far Future and the Ultra-Ultra Far Future.

The past and the present ocean engineering activities are described in the books of RINA and SNAME. The near future ocean engineering activities are outlooked in the books of National Research Council of USA (2013), DNV (2014) and National Research Council of the National Academies of USA (2011).

In the following, the past and present ocean engineering activities are briefly introduced. The future outlook of ocean engineering activities are focused mainly on floating ocean platforms. The reason why floating ocean platforms are focused is the ocean activities which have been developed mainly on floating platforms which include ships and fishing vessels and oil rigs.

In the following, the time axis starts at the Age of Great Navigation when ocean going vessels were built.

The Past begins at the Age of Great Navigation and covers the time till the oil crisis in 1973 or 1978.

The Present covers the time from the oil crisis to the beginning of the 21st century.

The Near Future includes the time in 50 years later.

The Far Future covers the time when the sea level rising causes the difficulty of residence on land.

The Ultra Far Future corresponds to the time which will last for 20,000 years in the Inter-glacial Period and to the time of the Glacial Period at least 80,000 years later.

The Ultra-Ultra Far Future corresponds to the time when the living things on the Earth be disappeared since the Sun approaches too close to the Earth. Then the evacuation from the Earth may be the most important issue.

Almost all the key words in this paper will be refered to the corresponding internet web sites.

2 OCEAN FIELDS FOR OCEAN ENGINEERING ACTIVITIES

According to the Ocean Culture Theory written by Boeckmann (1924) the ocean field can be categorized to four groups, such as, the ocean field of resources, the ocean field of space utilization, the ocean field of crossing power and the ocean field of experience.

2.1 *Ocean field of resources*

The resources in the ocean include fishery resources, oil & gas, ocean minerals and metals, renewable ocean energy, water, salt, lithium, uranium and so on.

2.2 *Ocean field of space utilization*

The ocean field of space utilization includes ocean transportation, submarine pipeline, submarine cable, underwater acoustic communication, storage of oil, ocean city, ocean airport, floating harbor and so on.

The ocean covers coastal zone, wetland, underwater, subsea, deep-water, sub-bottom, territorial waters, EEZ, and high seas. The ocean functions a stockyard of necessary resources for human being.

2.3 *Ocean field of crossing power*

The ocean field of crossing power includes military power, anti-symmetric war such as terrorism, natural disasters (typhoon, hurricane, storm surge, earthquake, tsunami), global warming, ocean acidification, artificial disaster (oil spill, environmental pollution), and so on.

2.4 *Ocean field of experience*

The ocean field of experience consists of tourism, cruising, swimming in the ocean, diving, surfing, sailing, water front leisure, recreational fishing and boating (pleasure boat), discovery, nature observation, exploration of new frontier such as deep water or polar area and so on.

3 PAST OCEAN ENGINEERING ACTIVITIES

3.1 *Age of great navigation and industrial revolution*

In the past at the Age of Great Navigation, there were two important industries, those are, fishery industry and ocean transportation such as shipping. The crossing power was also important.

A Portuguese Carrack ship such as 3 or 4 masted sailing ship brought a first gun (matchlock) to Japan in 1543. The gun symbolized the western culture and western technology for Japan at that time. The Cutty Sark was the last cargo sailing ship which transported tea from Shanghai to London. A sailing ship was a real Green Ship powered by renewable energy "Wind" with zero CO_2 emission.

Since the Industrial Revolution, vessel powering system achieved great progress. The powering system was changed from wind power or human power to steam engine or diesel engine. The materials of vessels were also improved from wood to iron or steel. The Blue Ribbon award for the Atlantic cruise vessels and naval war ships had been playing a leading role for the development and innovation of ocean engineering activities, especially in the first half of the 20th century.

3.2 *After World War II*

Since the World War II, the navy technologies were transferred to shipbuilding industries some examples of which were welding and block construction. This kind of technology transfer is called as "spin-off", while nowadays "Commercial On The Shelf (COTS)" and "dual use" are popular for the development of navy vessels and facilities. Underwater acoustics developed by naval researches, was applied to fisheries and ocean science observation research vessels. Radar and GPS (Global Positioning System) developed by military researches were applied to ship navigation systems.

After the World War II, from the stand point of shipping, container transportation, ultra large tankers, ultra large bulk carriers are one of the shipping revolutions.

Offshore oil & gas development has been one of the most important ocean engineering activities after the World War II, especially after the oil crisis in 1973 & 1978. Offshore oil exploration with seismic technology, directional drilling and subsea production system are three key technologies for offshore oil & gas activities. And also development of offshore structures which are fixed or floating in shallow water or deep water is remarkably progressed on design, construction, installation and operation with safety, reliability and environmentally acceptable.

3.3 *Computer revolution*

After the World War II, the ocean engineering activities have been dramatically improved and progressed in the four groups of the ocean field, depending on various revolutions such as fuel revolution from coal to oil, electricity revolution, computer revolution and information revolution.

Computer revolution is a remarkable epoch to innovate design, construction, installation, operation, maintenance and decommissioning of offshore structures besides transportation vessels.

With regard to designing safety, reliable and efficient offshore facilities, computer simulation model test, experimental model test, prototype model test and full scale in-situ test are required.

Computer simulation is applied to not only hydrodynamic analysis, structural strength analysis, but also thermodynamics and fracture mechanics. The computational method developed so far is categorized into five groups which are "Eigen function Expansion Method (EEM)", "boundary integral method", "Finite Element Method (FEM)", "Finite Difference Method (FDM)" and "Discrete Element Method (DEM)". Each computational methods have various their own branch methods.

In the future, the network revolution with internet will play a very important role for ocean engineering activities.

3.4 *Creative failure*

Accidents may play an important role for progressing technologies. Examples of maritime accidents called as creative failure are as follows: Titanic in 1912, Torrey Canyon in 1967, Alexander Kielland in 1980, Ocean Ranger in 1982, Exxon Valdez in 1989, Piper Alpha in 1988, Estonia in 1994, Deepwater Horizon in 2010 and so on. These creative failures have introduced international maritime regulations on life saving, safety, environment, or sustainability, such as SOLAS, MARPOL, MODU Code, London Convention and so on at IMO.

4 PRESENT OCEAN ENGINEERING ACTIVITIES

The state of the art ocean engineering activities are reflected in the industries which belong to each ocean fields.

4.1 *Ocean field of resources*

The active industries belong to mainly offshore oil & gas and ocean renewable energy. The fishery faces now a difficulty of overfishing since fishing vessels are equipped with efficient fishing gears and advanced monitoring systems. The state of the art of the aquaculture is the Bio-Floc Technology (BFT).

Offshore oil & gas development goes to deeper and deeper close to 3000 m water depth. The riser dynamics is an important issue. Deepwater oil & gas fields are developed in GOM (Gulf of Mexico), Offshore Brazil and West Africa. New oil & gas reservoirs are found as subsalt or pre-salt reservoirs in Brazil and West Africa. The decommissioning of oil & gas rigs is another big issue. The number of oil & gas rigs around the world is about 6000, while among them 4000 are in GOM. In GOM, new comer rig number is about 120, while the number of retired decommissioning rig is about 120.

4.2 *Ocean field of space utilization*

The active industries belong mainly to shipping. The size of vessels are getting larger and larger which are called as Panamax or Suezmax. A container vessel may be over 18,000 TEU. Hydroelasticity, fatigue of high tensile stress steel material and water-tightness of big propeller shaft may be big issues.

The logistics play important roles on the world trade. Competition of air, sea and land transportation is big issue. The larger the ship be, the deeper water depth the port and harbor facilities be required. More than 20 m water depth is required at the berth for a largest container vessel. Since it is not easy to construct such deep water berth, then a VLFS type floating berth may be used in future.

Energy saving and environmentally-friendly development are also another big issues. In order to remove uncertainty on sea trials, IMO requires EEDI/EEOI.

The Mega-Float project (2000) which lasted for 6 years proved that a VLFS (very large floating structure) airport is technically feasible, even offshore.

4.3 *Ocean field of crossing power*

Navy ships require stealthiness, cost performance, quietness on propeller noise, biofouling removal, energy saving and so on. Unmanned navigation system is a big issue. The navy technology may try to adopt COTS, Dual Use and Spin-off. The welding for submersibles and the nuclear power plant on ships are other high technologies in the navy side.

Counter measures for natural disasters have been big issue for tsunami and storm surge since

Figure 1. Mega-float—phase 2 project (Megafloat, 2000).

Indian Ocean earthquake and tsunami in 2004, North East Japan great earthquake in 2011, and Hurricane Katrina in 2005, respectively.

4.4 *Ocean field of experience*

Cruising is one of the most popular activities in the field of experience. The popular cruising routes are Caribbean cruise, Mediterranean cruise, Vancouver-Alaskan coastal cruise, Scandinavian coastal cruise, South East Asian cruise, South Pacific cruise and so on. The biggest cruise ship is now around 400 m long, 200,000 Gross tonnage and over 5,000 passengers.

In 21st century, sustainable development becomes an important key issue due to the limits to growth (Meadows, et al, 2004) reminded by limited resources such as fossil fuel. Moreover the sea level rising due to the global warming becomes another important issue. Ecosystem protection and restoration for coastal zone and wetland are also big issue now.

4.5 *Innovation*

In 21st century, productivity of process line has been quite improved. 3D CAD, CAM, PDM are already introduced into a factory automation. The design method is changed from "design spiral" to "holistic design". The process innovation has made remarkable progress, while product innovation, organization innovation and marketing innovation have been also improved.

5 NEAR FUTURE OCEAN ENGINEERING ACTIVITIES

In the following, main industries in each ocean field are selected for describing near future ocean engineering activities.

5.1 *Ocean field of resources*

The main issues for the oil & gas industries may be ultra deep-water, pre-salt reservoir and arctic. Ocean mineral resources such as manganese nodule, cobalt rich crust and ocean rare metal or rare earth may be far from commercial subjects even in the near future. Methane hydrate will be also in the same situation as the ocean minerals.

Worldwide monitoring and management of fish species will be the main issue for the fisheries, in order to avoid the overfishing. Aquaculture will be another solution after solving problems on economical feeding, development of vaccine for diseases and fries of main fish species.

It is important to understand the ocean must be reservoir of food, energy, minerals, water and CO_2. The ocean may be the huge storage of oil & gas, methane hydrate, rare metals around hot spot, rare earth, manganese nodule, cobalt rich crust, uranium, lithium, and water.

5.2 *Ocean field of space utilization*

With regard to vessel transportation, full automatic unmanned navigation and full automatic cargo handling at a port will be the main issues. Worldwide logistic system will be organized in the network of air, boat and track with fully automatic unmanned system.

Worldwide submarine cable system will be completed and underwater GPS system will be available.

Since the prototype model test of the 1000 m long Mega-Float as a floating airport was successfully done, a floating city may be technically feasible. At the present, an offshore floating structure is used not only for offshore oil & gas production, but also for a launching platform of a satellite rocket [Sea Launch] and for oil storage barges.

5.3 *Ocean field of crossing power*

With regard to war ships, still automatic unmanned system, stealthiness and quietness may be the key issues. However, the military power hopes to be disappeared and the world will be out of war in the near future, according to Dawkins's theory based on Darwin's natural selection. According to "The Selfish Gene" written by Dawkins (2006). The selfish gene of a human being will avoid war in order to save the human being itself under the nuclear power deterrent.

Countermeasures for natural disasters will be floating platform which are resilient for earthquake and tsunami. A floating platform will be applied to a nuclear power plant, disaster relief base, emergency hospital, fuel stock yard and so on.

5.4 *Ocean field of experience*

Cruising may be more popular in near future. There is a proposal of cruising around the world in two years (Freedom Ship). Retirement generation may enjoy the cruising around the world.

There will be some conflicts among stakeholders in coastal and wetland area where recreational fishing and boating may be popular and where regional ecosystem and protection and restoration are required under the ecosystem based management.

5.5 *Smart industry*

The LCE (Life-Cycle Engineering) will be a key issue for industries in the near future. The some examples of the LCE components may be 3D CAD, CAM, PDM, PLM and so on. Factory automations will be based on the open network. A VLFS may be maintained safely, environmentally and rationally. The LCE includes concepts of commissioning and decommissioning, concept of product lifecycle management, concept of engineering design & engineering management and so on. A VLFS consists of (Conceive, Design, Implement, Operate) or (Conceive, Design, Realize, Services) or more detail (Conceive, Design, Procure, Assemble, Construct, Install, Intervene, Operate, Maintain, Inspect, Repair, Replace, Refurbish, Decommissioning, Salvage, Reuse, Recycle, Abandon and Dispose).

Recently new holistic innovation is proposed as smart factory (Industry 4.0) by Germany.

6 FAR FUTURE OCEAN ENGINEERING ACTIVITIES

6.1 *Floating ocean city*

The global warming will affect the sea level rising and the residential area on land will be flooded. Then ocean floating cities will be necessary to keep the residential area stable. The NU Float (Masuda, 2009) proposed by the Nihon University in Tokyo is a floating city for Kiribati which is islands country on the equator of the middle of the Pacific Ocean. The capital city of the country faces the crisis of flooding due to the global warming and the sea level rising. The population of the floating city is 100,000, which is the same number of the population of Kiribati.

Venezia in Italy is the most famous ocean city the population of which is around 100,000 and the area is about 5 km^2. The area 5 km^2 is similar to the Kansai International airport in Japan the size of which is 5000 m × 1000 m. When a floating type Kansai Airport was proposed, the conceptual design of which proved that such kind of floating airports are technically and economically feasible. The Mega-Float project proved that a prototype model of a 1000 long floating airport is technically feasible.

6.2 *NU Float and a floating ocean country*

The NU Float has the area of 5 km^2 (=5,000 m × 1,000 m) to which the whole population of the Republic of Kiribati 100,000 can evacuate from the original island and on which they continue to live. The area of the NU Float is similar to the area of Venezia in Italy and Kansai Offshore Airport in the Osaka Bay in Japan. The NU Float (Fig. 2) is designed with enough city planning in which necessary urban facilities are settled. From the stand point of the seascape, a

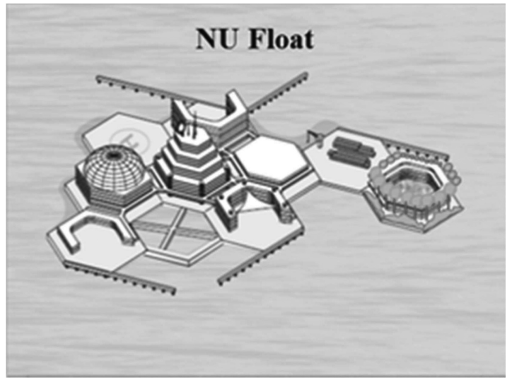

Figure 2. The NU Float with propagating floating units (Masuda, 2009).

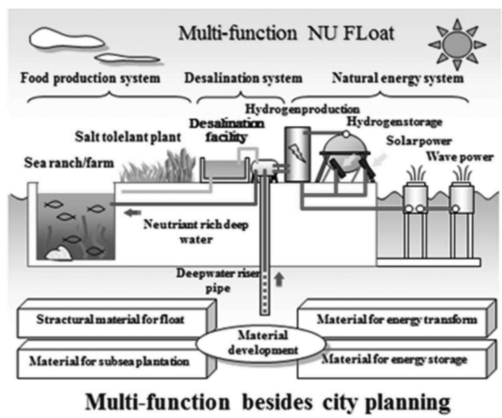

Figure 3. Multi-function of NU Float (Masuda, 2009).

hexagonal floating unit is adopted with 1000 units of which the NU Float consists of as a propagating unit. The NU Float is designed according to the general city planning which includes public infrastructures, transportation system, water and sewage facilities, schools and hospitals, disposal facilities, security and disaster precaution system and so on.

Besides the general city planning, the NU Float will develop the R&D frontiers on the NU Float which are the strategies of drinking water, food, energy and new materials, respectively, which are necessary to maintain the living of 100,000 nations. (Fig. 3).

Strategy of drinking water is Development of new desalination procedure.

Strategy of food is Development of rice hydroponics of sea water, sea water aquaculture on the NU Float, and aquaponics which is the integration of hydroponics and aquaculture in the closed circulation system.

Strategy of energy is Development of hydrogen energy storage system with solar or wave renewable energy devices and the intelligent grid system or smart grid system applied to the NU Float.

Strategy of new materials is Development of simpler procedure of synthesis of molecular magnetic substance in supercritical environment utilizing deep water high pressure and hydrothermal high temperature. The molecular magnetic substance will be used to develop new structural material for NU Float such as cracking self-detect and self-repair concrete.

The NU Float is technically feasible, while the feasibility of economics and politics is not yet clear at this moment. The NU Float seems to be a "New Noah's Ark".

The NU Float is a kind of closed cycle systems for living.

7 ULTRA FAR FUTURE OCEAN ENGINEERING ACTIVITIES

Within 20,000 years from now on, all the ice in Arctic and Antarctic ocean may be melt because of the global warming due to CO_2 emission. Seventy percent of the residential area on the continents of the Earth may be flooded. The most people on the Earth may lose their houses. In order to save the people who lose their houses, it is technically feasible to build Very Large Floating Structures (VLFS) as floating cities, since the prototype model test of 1000 m long Mega-Float was successfully done.

After 80,000 years later, the global warming will be changed to the glacial period, Ice Age. There will be no residential area exist on land available. If floating cities are located along the equator on oceans, then residential area will be realized. The total size of a floating city be 200 km × 3000 km, population of 10 billion will be available. The cost may be $15 T. This kind of a floating ocean city/country can be called as a "Floating Ocean Great Wall" or "Giga-Float".

8 ULTRA-ULTRA FAR FUTURE OCEAN ENGINEERING ACTIVITIES

After 500 million years later, the sun will approach to the Earth, then, living things on the Earth must become extinct. If a human being hopes to continue to live, he must evacuate from the Earth and go to a space colony, in order to continue to live. There is a proposal for a human being to evacuate to space, which is a space elevator. The best starting point of the space elevator may be a floating ocean platform on the Earth.

9 CONCLUSION

In the past, the present and the future, ocean engineering activities are surveyed and outlooked. Since the navy technologies were transferred to the civilian activities after the World War II, the ocean engineering activities were made great progress.

The ships have been becoming larger, faster with high quality. With the electronic revolution and the computer revolution, great progress has been made on safety and high functionality of the ocean engineering activities.

Considering hydro-elasticity, a construction of ultra large container vessels and a VLFS (very large floating structure) are available.

In the near future, people expects to realize green-ships or floating ocean cities in order to recover lost residential area due to high sea level rising.

In the ultra far future during the Interglacial period which lasts 20,000 years, the sea level rising will come to the peak when all the polar ices are melt. More than 70% of residential area of almost all countries may be lost. In order to avoid this kind of risk, every country in the world may require floating ocean countries called as a New Noah's Ark.

After the Interglacial period, the Glacial period may come and last 80,000 years. It will be too cold to live on land. Residential condition in the Glacial period may be worse than that in Interglacial period. Only residential area on the Earth may be the ocean area along the equator. "Giga-Float" which is larger than "Mega-Float" installed along the equator on oceans will be required. The Giga-Float can be called as The Floating Ocean Great Wall.

500 million years later from now on, the Sun becomes hotter and the biosphere and the human being on the Earth may extinct. Then the human being will evacuate from the Earth to the space colony with a space elevator. The best starting point on the Earth for the space elevator will be a floating ocean platform installed along the equator of oceans.

Contingency plan is necessary for the human being to intend to continue to live at any time along the time axis.

The main issue of the contingency plan must be a floating ocean platform.

In the future from now on, the development of the floating ocean platform will be the main issue of the ocean engineering activities.

The concept of New Noah's Ark and Floating Ocean Great Wall were used as the example of "Macro Engineering" by Maeda and Kada (2004).

The idea of floating ocean city was found in the SF novel written by Jules Verne (1897, 2013) about 120 years ago.

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Risk assessment for ship collisions against offshore structures

P. Terndrup Pedersen
Department of Mechanical Engineering, Technical University of Denmark, Denmark

ABSTRACT: Offshore installations served by in-field vessels and/or situated in the vicinity of ship traffic lanes are exposed to collision hazards such as risk of loss of life, economic loss, and environmental damage. Therefore, one of the many performance goals in the design phase of such structures is to ensure that the risk for major accidents and service disruptions is low enough to be acceptable to users, the public and those responsible for public safety. The collision risk hazards must also be re-evaluated at proper time intervals during the operational phase in order to update the risk estimate due to changes in ship traffic in the vicinity of the offshore structures and new developments within navigational equipment and procedures. The paper highlights some of the available analytical elements in collision frequency estimation and response calculations for different types of offshore installations and indicates how these tools can be applied to evaluate relevant risk control options.

1 INTRODUCTION

Risk analyses have to be carried out for installations such as: Offshore structures for extraction of hydrocarbons, Offshore wind farms, Bridges spanning navigational channels and for similar structures built offshore. The purpose of such risk analyses is to estimate hazards such as: Number of fatalities, Pollution to the Environment, and loss of Property or Financial exposure.

Offshore oil exploitation activities involve many types of risks, see Moan (2009), and collision between ships and platforms has been pointed out as one of the major risks. An offshore oil installation may be hit by by-passing ships, by infield vessels such as tankers involved in offshore loading and by supply ships in operation close to the installation.

Collisions with supply vessels are the most frequent types of collisions and for these collisions the consequences for the structural integrity of the platform should be small. Most rules and regulations (for instance NORSOK N-400) specify that for structural design purposes the mass of the colliding supply ships should not be selected less than 5000 tons and the speed not less than 0.5 m/s for the Ultimate Limit State (ULS) design and 2 m/s for Accidental Limit (ALS) design checks. Today's supply vessels are gradually growing in size and several supply ships have displacements around 7500 tons. An accidental collision with a large supply vessel with considerable speed may therefore lead to an emergency case which can have large economic and environmental implications. As a consequence, offshore units such as FPSOs, semisubmersibles, jackets and jack-ups may in the future have to be capable of absorbing higher impact energies than specified in the codes and standards from the past.

Oil tankers for offshore loading will in the loaded case have displacements in the order of 100 000 tons, so also in this case can the collision energy be quite large even for small impact velocities.

Collisions with by-passing ships should be events with very little probability since the energy released for damage of the installation and/or the ship can be very high and the consequences catastrophic.

Table 1 reproduces accident data which shows that the most severe collision accidents against oil installations are caused by impact from passing vessels and that accidents caused by in-field vessels are more frequent and at the same time of less severity. The world statistics show that the annual collision risk per platform is around 10^{-3}. Of course, this probability depends very much on the location of the installation. Statistics from the UK sector in the North Sea show accident rates which are one magnitude higher Sii et al. (2003). This may be due to better reporting and/or more ship traffic in the vicinity of the installations.

Offshore installations are not all oil related. In Europe a large number of offshore windmill farms have been or are being built close to areas with considerable ship traffic. Also wind turbines require regular visits from service vessels. For these installations the authorities require Environmental Impact Analyses (EIA) to be performed which includes risks from ship collisions, Pedersen (2013).

Table 1. Worldwide statistics for ship collisions against offshore oil installations during 1980–2002. Reproduced from: Risk Assessment Data Directory, International Association of Oil & Gas Producers. Report No. 434/16 March 2010.

Damge*	Passing vessels		Infield vessels	
	Number	Percent	Number	Percent
Total loss	3	5%	1	0.5%
Severe	19	33%	16	8%
Significant	8	14%	55	29%
Minor	10	18%	65	34%
Insign./no	17	30%	52	28%
All	57	100%	189	100%

Vessel type	Collisions		Exposure (installation-years)		Collision frequency (per installation-year)	
	1980–1989	1990–2002	1980–1989	1990–2002	1980–1989	1990–2002
Passing	33	24	56243	97627	5.9×10^{-4}	2.5×10^{-4}
Infield	103	86			1.8×10^{-3}	8.8×10^{-4}

Bridges crossing international sea routes or bridges crossing major rivers with heavy ship traffic also have to be designed such that the risk for interruption of the link due to ship impacts is tolerable. Again this includes a consistent evaluation of the ship collision risk. Pedersen (2002).

Ship impact analyses for offshore installations are not only required during the design phase. Around Europe a Safety Case has to be prepared for all oil offshore installations at regular intervals, for example every five years, in order to demonstrate that the installation meets safety and legal requirements. Part of this Safety Case is a quantitative assessment of the collision risk.

To evaluate the threat that an offshore installation is hit by a passing ship or an infield vessel a proper mathematical procedure must be available. It is the purpose of this paper to present elements in such an evaluation procedure.

The first part of the paper deals with a model for calculation of the probability that a passing ship collides with a given offshore installation. This model is based on a collection of basic information of ship traffic in the area and the navigational arrangements around the platform.

The second part of the paper deals with calculation procedures to estimate that part of the initial kinetic energy which is available for crushing of the ship and the offshore installation in a given collision scenario. Part of the initial kinetic energy of the colliding ship will normally still be present as kinetic energy after the collision event and part of the energy may be transferred to elastic energy in the struck structure. The purpose of this analysis is to determine the probability distribution for the remaining impact energy that has to be absorbed by crushing of the ship and/or platform.

The third part of the paper deals with damage calculations when the energy released for crushing has been estimated. The distribution of damages between the impacting ship and the offshore installation is discussed and simplified force—penetration relations for ship structures are presented.

Finally, it is briefly shown how the discussed calculation tools can be assembled into a Monte Carlo simulation procedure for estimation of the probability of failure given a collision has taken place.

2 PROBABILITY OF SHIP IMPACT

To perform a consistent quantitative risk analysis of offshore installations exposed to ship collisions from passing ships a first step is to collect background information such as: Seabed bathymetry, Installation geometry and position, Present and Future ship traffic characteristics and volume, Navigational routes in the vicinity, Spatial distribution of ship traffic, Wind, Current, and Ice conditions, etc.

2.1 *Estimation of present ship traffic*

The present ship traffic and the spatial distribution of this traffic can be obtained from the compulsory Automatic Identification System (AIS) and from radar observations (Silveira et al. (2013), Gluver & Olsen (2001) and Mou et al. (2010)). See Figure 1.

Based on collection of AIS data detailed information on passing ship traffic can be stored in a database and subdivided into the ship type categories such as: Bulk carriers, Chemical tankers, Container vessels, Gas tankers, Oil tankers, Passenger vessels, Ro-Ro vessels, and Other vessels

Each of these categories can be further subdivided into a number of ship size classes. See Table 2. Each ship class is defined by the following average properties: Length, Breadth, Depth, and for both loaded and ballast conditions: Speed, Draught, Displacement, Height of deck, and Height of bulb.

The present ship traffic must afterwards be modified to account for the development in ship traffic during the lifetime of the installation.

As predicted by the traffic intensity theory the arrival times of ships at positions close to the installation can often be modelled as a Poisson process. That is, the random arrival frequency at the bridge line is approximately given by:

$$p(x) = \exp(-\lambda)\lambda^x/x! \quad (1)$$

where
x = No of vessels/hr, and
λ = Hourly average.

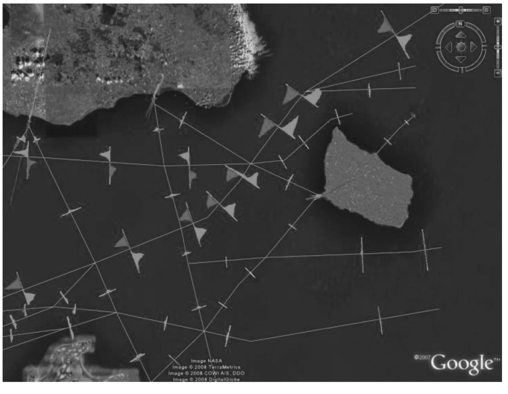

Figure 1. Ship traffic distribution obtained from Automatic Identification System (AIS).

2.2 *Probability of ship collision events*

Knowing the composition of the passing vessels we shall briefly describe the factors, which influence the probability of ship impacts against offshore installations. Most of the existing mathematical models are based on calculation of the number of collision candidates in the case of blind navigation and a subsequent use of causation factors to model the action of the navigators on board the ships, Fujii et al. (1974) and Ståhlberg et al. (2013). That is, the collision frequencies $N_{ship\text{-}ship}$ are estimated as the number of collision candidates N_a multiplied with causation factors P_c:

$$N_{ship\text{-}ship} = P_c N_a \quad (2)$$

The model for estimation of the number of collisions in the case of blind navigations, N_a, is based on a division of the ship collision problem into a number of different phenomena and subsequent application of mathematical models for quantification of the risk from each category, Pedersen (2002).

Category 1: Ships following the ordinary, straight route at a normal speed and with a normal ship track distribution. See Figure 2. For this category the expected number $N_{Cat,1}$ of blind collisions per unit time T can be determined from the expression:

$$N_{Cat,1} = \frac{1}{T}\sum_{\substack{Ship\\class}}^{n} \int_{z=A}^{B} \int_{t=0}^{T} q_i f(z) B_i(z) dt\, dz \quad (3)$$

here q_i is the traffic density function of class i ships given by the number of ships, $f(z)$ the spatial distribution, and B_i is a simple geometrical collision indicator function, which is 1 when the ship strikes the platform.

Category 2: Ships which fail to make a proper change of course at a turning point in the vicinity of the installation. To determine the added probability for ship collisions in the vicinity of bends of

Table 2. Example on part of database for passing vessels.

Ship types	Ship size class 1	2	3	4	5	6	7	8	9
Cargo	0.0%	9.1%	30.2%	40.7%	53.9%	49.6%	61.1%	79.2%	0.0%
Tanker	6.5%	0.0%	64.2%	57.6%	46.1%	49.6%	36.7%	10.1%	100.0%
Passenger	3.2%	0.0%	0.0%	0.0%	0.0%	0.0%	2.2%	10.7%	0.0%
Fishing	32.3%	36.4%	1.9%	1.7%	0.0%	0.8%	0.0%	0.0%	0.0%
Assisting	54.8%	9.1%	3.8%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Other	3.2%	45.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%

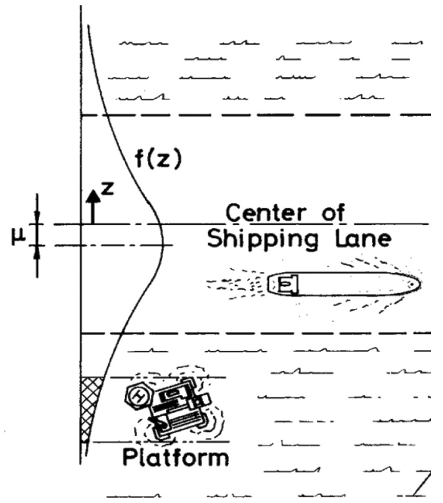

Figure 2. Collision candidates from category 1.

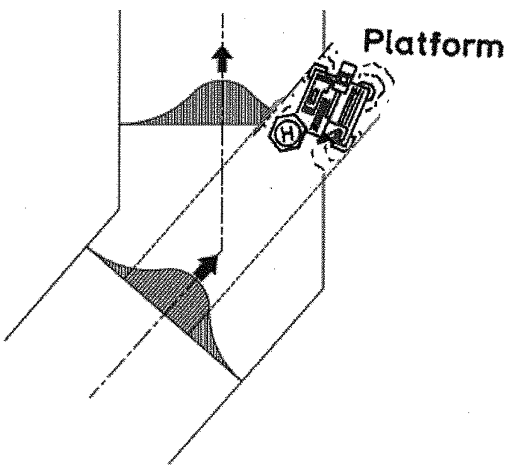

Figure 3. Collision candidates from category 2.

the seaway, see Figure 3, where the vessels may not make the turn a procedure similar to the one used for Category 1 can be used provided that the procedure is augmented with the probability that the ships fail to act on the changing route direction. The probability that a ship fails to change course at a turning point can for example be modelled as

$$P_T = P_c P_0^{(d-a)/a} \tag{4}$$

where P_c is the causation probability due to human errors or technical failure as indicated in Eq. (2) and P_0 is the probability of omission to check the position of the ship, d is the distance sailed on wrong track and a is the average sailing length between position checks by the navigator.

Category 3: This category includes passing ships which do not follow the ordinary route recommended in charts, ships drifting due to mooring or anchoring failures, drifting ships at work such as infield vessels and fishing vessels, and ships drifting due to loss of propulsion. For drifting passing ships or ships with rudder failure it is normally assumed that the ships at the time of loss of propulsion are located on the idealized sailing route. When the probability distribution for the duration time for black out and the current and wind distributions are known the probability of collisions can be estimated.

The causation factor P_c depends on those technical, environmental, and human factors which have an effect on the avoidance of a collision. The causation probability P_c can be estimated on the basis of available accident data collected at various locations and then transformed to the area of interest. Another approach is to analyze the cause leading to human inaction or external failures and set up a fault-tree procedure. Based on observations Kaneko and Hara (2007) and Itoh et al. (2007) have shown that for ordinary ship traffic the causation factor P_c is in the range 0.5 10^{-4}–3 10^{-4}. Calculation procedures based on a Bayesian Network method for calculation of P_c as function of bridge layout, manning etc. have also been presented in the literature, see Hänninnen & Kujala (2012).

Having estimated the probability of ship-ship collisions further data is needed to estimate the distributions of collision speeds, angles and collision locations in order to derive collision energy distributions. These collision variables depend on the aversion procedures taken by the involved navigators up to the event and since so far no mathematical models have been proposed for these quantities such collision variables have to be based on empirical statistical data.

When the collision probability is estimated for a given installation then the probability that different parts of the structure is being hit can be estimated by geometrical considerations. For example, for a head-on bow collision the probability of hitting a specific pier area, see Figure 4, given a collision on a certain ship course β is

$$F_{area1} = \frac{d_1 + 0.5B}{\sum_j d_j + B},\ F_{area2} = \frac{d_2}{\sum_j d_j + B}$$

$$\text{and } F_{area3} = \frac{d_3 + 0.5B}{\sum_j d_j + B} \tag{4}$$

That is, the total annual probability of collision on the face j of a certain pier No. i is $F_{icollj} = F_{areaj} \cdot F_{icoll}$,

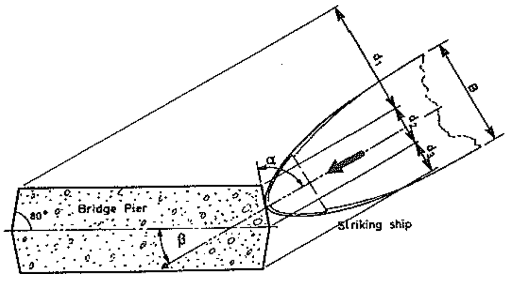

Figure 4. Head on collision against a bridge pier.

where F_{icoll}, is the total yearly collision frequency for the considered pier. Each of the pier areas j are characterized by a certain striking angle α.

2.3 *Control options for collision risk*

With mathematically based analytical tools such as those described above where the causation factor is based on either a fault tree or a Bayesian network based approach it is possible to analyse the effect of Risk Control Options (RCO) such as:

Change in collision probability from passing vessels:
- New vessel routing in the vicinity of the installation
- Increased safety zones
- Alarm/VHF communications with vessel
- Emergency procedures if vessel is on collision course

Change in causation factor due changes in human behavior on in-field vessels:
- Effects of manning
- Effect of simulator training
- Effect of psychological screening of navigators

Changes in infield vessel design such as:
- Improved Bridge layout and technical equipment
- The effect of redundancy of navigational equipment
- Effect of ship speed on causation factor (time to react)
- Effect of improved maneuverability on causation factor (time to react)
- Effect of reduced probability of engine blackout or rudder failure
- Effect of reduced time for power recovery.

3 DISTRIBUTION OF ENERGY RELEASED FOR CRUSHING

When the probability of ship impacts of the different ship classes against the offshore installation is known, the next step in the risk assessment procedure is to determine the probabilistic distribution of collision energy released for crushing given a collision has taken place.

Standards within the petroleum industry for design against ship collisions are based on the assumption of central impacts where the collision force vector points through the center of gravity of the installation as well as the ship. This is a very conservative assumption.

First of all collisions are rarely central collisions. Therefore, after the collision the colliding ship will still have some translational as well as rotational kinetic energy. Secondly, for collisions against flexible offshore installations such as bottom supported wind turbines, steel jackets and jack-ups part of the available kinetic energy can be transferred into elastic deformation energy. For impact against solid gravity supported structures energy can be spent in minor sliding of the structure, and for ship collisions against floating offshore platforms energy can be transferred to translational and rotational motions of the hit floating structure. For these reasons it is normally much too conservative to use simply the initial kinetic energy of the ship to represent the energy which needs to be dissipated by structural damages.

3.1 *Effect of non-central impacts against rigid structures*

To demonstrate a more realistic approach we shall first assume that the impact force F_c is perpendicular to the ship waterline with slope α as shown in Figure 5. Further, we shall assume that it is sufficient to assume that the effect of water pressure on the hull surface of the colliding ship can be approximated by the added mass at infinite frequency. Then the initial kinetic energy of the colliding vessel is:

$$E_o = \frac{1}{2} M_s \left[\left(1 + m_{xx}\right) \sin^2 \alpha + \left(1 + m_{yy}\right) \cos^2 \alpha \right] V_o^2 \tag{5}$$

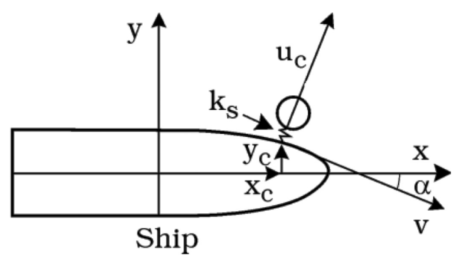

Figure 5. Ship impact against a tubular member.

provided the initial translational velocity in the impact direction is V_o, the mass of the ship is M_s, and the constant added mass coefficients are denoted $m_{xx} = M_{xx}/M_s$, $m_{yy} = M_{yy}/M_s$ for surge and sway motions, respectively.

However, only a part of this energy will normally be released for crushing of the involved structures. For non-central impacts the ship will still have kinetic energy left in sway and yaw motions at the end of the impact. It can be shown, Pedersen & Zhang (1998), that for non-central impacts against a rigid structure the loss in kinetic energy is reduced to

$$E_{kin} = \frac{1}{2}\frac{M_S}{D_s}V_o^2 \qquad (6)$$

where the mass correction D_s due to eccentricity and the added mass effects is given by:

$$D_s = \frac{1}{1+m_{xx}}\sin^2\alpha + \frac{1}{1+m_{yy}}\cos^2\alpha + \frac{1}{1+j}\frac{\left[y_c\sin\alpha - (x_c - x_g)\cos\alpha\right]^2}{R^2_s}$$

Here the collision point (x_c, y_c) is measured in the water plane from the centre of gravity of the ship and j is the added mass coefficient for yaw motions and the mass moment of inertia is $I_z = R_s^2 M_s$.

For different impact locations along the hull of a typical supply vessel Figure 6 shows the energy ratio defined as the loss in kinetic energy after a collision against a rigid tubular structure in a direction perpendicular to the ship waterline, given by Eq. (6), and the total ship kinetic energy before impact, given by Eq (5).

3.2 *Effect of glancing impacts*

A basic assumption behind Eq. (6) is that the collision force is perpendicular to the ship surface, i.e. sliding or glancing does not take place. Figure 7 shows how the energy released for deformation and crushing is reduced for oblique collisions against rigid surfaces for two different coefficients of friction. For collisions against FPSOs and concrete structures such as bridge piers, see Figure 4, the effect of sliding can reduce significantly the amount of energy which needs to be absorbed by structural crushing.

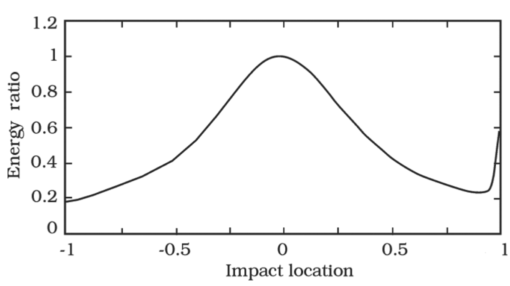

Figure 6. Effect of impact location for ship impacts perpendicular to the ship waterline.

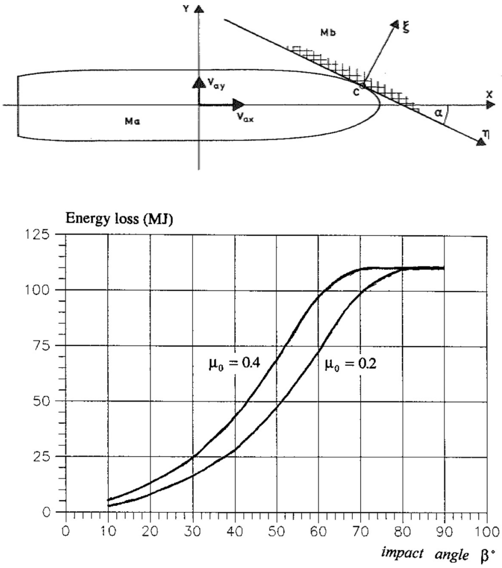

Figure 7. Head—on collisions against a rigid wall: Energy released for structural damage as function of impact angle and for two different coefficients of friction. Pedersen & Zhang (1998).

3.3 *Effect of structural flexibility and non-central collisions*

When the collision strength of installations is analyzed the applied structural model (often FEM) is normally restricted to a very local area often simply one tubular member with elastic supports representing the flexibility of the surrounding structure. That is, these calculation models do not include the energy which can be stored in elastic deformations of the global structure. However, for collisions against offshore steel jackets, jack-ups, and offshore wind turbine structures where the mass of the supporting structure is relatively small compared to the topside mass and where the global stiffness is such that the lowest natural global vibration period is larger than the collision duration then a significant part of the available collision energy can be absorbed by overall vibration energy of the installation. That is, in these cases a considerable reduction of the energy to be spent for local crushing can be expected. This has been studied in Pedersen & Zhang (1998).

An example is shown in Figure 8 where a simulation is presented for an impact between a supply vessel of 2500 tons displacement collides with a small unmanned platform on 50 m water depth and a topside mass of 500 tons. The topside structure is not shown in Figure 8. The lower part of the figure shows the ratio of energy which must be absorbed by crushing for various impact locations along the hull. The impact direction is perpendicular to the hull surface. At collision location FP the impact is taken to be head-on. The upper curve in Figure 8 representing the energy ratio for the rigid structure is similar to the curve depicted in Figure 6. The lower curve represents the energy ratio when the structural flexibility is taken into account. It is seen that for this example a significant part of the available energy is spent for global dynamic deformation of the flexible tower structure. The consequence is that the energy to be spent by crushing of the colliding vessel or the platform is further reduced.

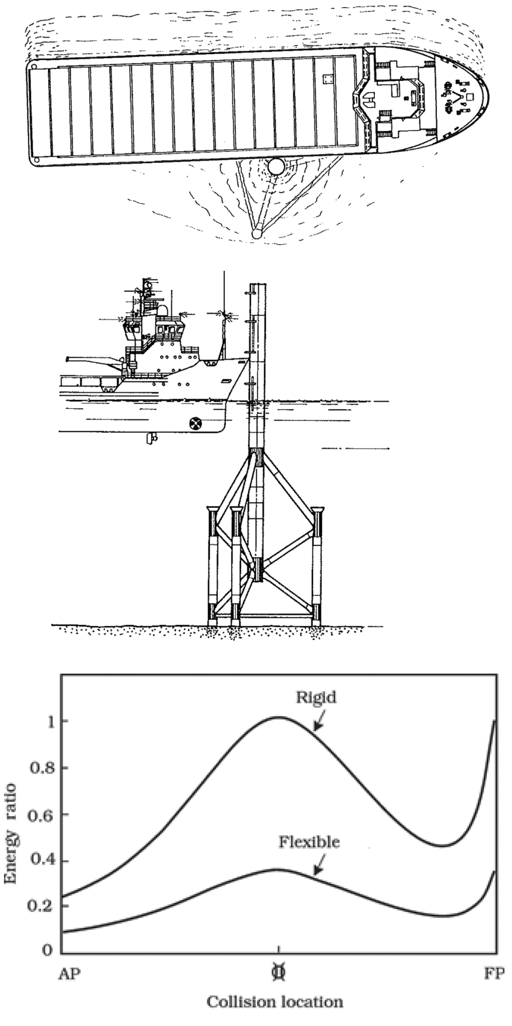

Figure 8. Energy ratio to be absorbed by crushing for a 2500 t supply boat impact at various locations on a small unmanned platform, curves are shown for a rigid structure and the actual flexible structure.

3.4 *Effect of non-central impacts on floating offshore installations*

The regulations for impact analyses for floating offshore structures (see NOSOK N-400 and DNV-RP-C204, 2004) such as semi-submersibles and FPSOs are all based on the assumption of central collisions where the force vector points through the center of gravity of the platform and the ship such that possible yaw motions of the two structures are neglected. In this case the loss in kinetic energy energy can be determined simply by the one-dimensional classical considerations of conservation of energy and momentum (Minorsky 1959) and the result for the energy to be absorbed by the platform E_p and by the ship E_s is found as:

$$E_s + E_p = \frac{1}{2} m_s v_s^2 \frac{\left(1 - \frac{v_p}{v_s}\right)}{1 + \frac{m_s}{m_p}} \qquad (7)$$

where m_s and m_p are the mass plus added mass of the ship and the platform, respectively, and v_s and v_p are the velocities.

It is obvious that the probability that the impact between two floating bodies is such that the impact force vector points through both centres of gravity is very small and in most cases the impact energy released for crushing will be much smaller than expressed by Eq. (7). For a more realistic calculation of the motion of the ship and the floating offshore structure, during the collision event one choice is time simulation, Sourne (2007). Another possibility is to use a simpler theory based on the classical rigid body dynamics. Such a simplified analytical procedure was presented in Pedersen & Zhang (1998) for the outer collision dynamics, i.e. for determination of the energy released for crushing during collision between two floating structures.

4 STRUCTURAL DAMAGES OF INSTALLATIONS AND SHIPS

When the distribution of the colliding ship types and sizes and the energy released for crushing are known, the next step in a consequence analysis is to determine the distribution of crushing damages to be absorbed by the ships and the installation.

The breakdown of damages between the involved structures depends on the relative strength of the ship structures and the impacted parts of the installation. See Figure 9. If the ship is assumed to be infinitely stiff and all the energy has to be dissipated by the installation, i.e. an assumed *ductile design* of the installation, a very conservative design of the installation structure is normally realized. Usually, it will be much more cost effective to take into account the finite strength of the colliding ships. Then both the striking ship and the installation may undergo local damage and absorb energy; in this case the design is said to be based on *shared energy.* If the strength of the platform is so large that the major part of the energy can be expected to be absorbed by the striking vessel then the installation is said to be *strength designed.*

As mentioned above most offshore standards contain requirements for the installations to be able to resist some impact from the largest infield or supply vessels serving the installation. Significant damage to the installation is allowed but it is a design requirement that the damage does not lead to progressive collapse of the structure. A very comprehensive guidance to the local design of offshore structures against collisions with supply vessels has recently been published by Storheim & Amdahl (2014). Here a critical review is also given of the often used code NORSOK N-004 and it is demonstrated that even fairly moderate modifications of the strength of the exposed members of the offshore installation can change the design to be based on strength

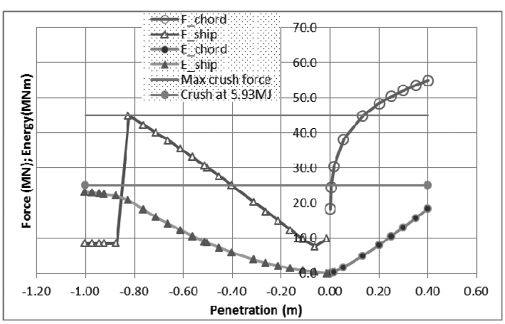

Figure 9. Force-penetration and energy-penetration curves for sideway crushing of an ice stregthened supply vessel and the chord of a jack-up leg (Note: penetrations of supply vessel are shown as negative values). Zhang et al. (2014).

such that major part of the energy is dissipated by the colliding ship and leaves little damage to the installation.

The distribution of passing vessels will normally be such that for the upper part of the size distribution it is not feasible to base the design of the installation on a strength design. That is, in order to determine the distribution of damages it is necessary to determine the crushing strength of the ship as well as the installation.

Since only distributions are known for the passing vessels it is not feasible to base the crushing strength of the ships on similar finite element analyses. Here simplified empirical expressions are needed for the crushing loads, expressions which are well suited to be part of Monte Carlo simulations needed to determine the damage distributions given a collision with a distribution of passing ships as indicated in Table 2.

4.1 *Empirical expressions for ship collision forces*

Collision forces, i.e. forces associated with crushing of the ship structure can be estimated by many different methods. The most detailed and comprehensive methods are based on Finite Element Analyses. See for example Lee et al. (2013). However, for risk analyses faster and easier analysis procedures are needed. The simplest procedures are those based on the Minorsky (1959) procedure where the absorbed energy and thus the integrated force curve are related to the volume of the crushed structure. A somewhat more complicated, but still simple method, is based on summation of the resistance of the structural strength components in the ship.

Based on the results of a series of numerical finite element analyses and more simplified calculations, an empirical expression was derived for easy estimation of the maximum bow collision loads in Pedersen et al. 1993. This expression accounts for the effect of strain rate, impact velocity, vessel loading condition, and vessel size. The effects of eccentric impacts and the limited width of the fixed structure are not included.

The expression proposed in the above reference for maximum values of head on bow collision loads for ice strengthened merchant vessels between 500 dwt and 300,000 dwt has the following form:

$$P_{bow} = \begin{cases} P_o \cdot \bar{L}\left[\bar{E}_{imp} + (5.0 - \bar{L})\bar{L}^{1.6}\right]^{0.5} & for\ \bar{E}_{imp} \geq \bar{L}^{2.6} \\ 2.24 \cdot P_o\left[\bar{E}_{imp}\bar{L}\right]^{0.5} & for\ \bar{E}_{imp} \leq \bar{L}^{2.6} \end{cases} \tag{8}$$

here

$\bar{L} = L_{pp} / 275\ m$
$\bar{E}_{imp} = E_{imp} / 1425\ MJ$

where
P_{bow} = Maximum bow collision load [MN]
P_0 = Reference collision load equal to 210 MN
E_{imp} = Energy to be absorbed by plastic deformations [MJ], see section 3.
L_{pp} = Length of vessel [m]

The empirical expression, Eq. (8), for the maximum bow collision force will often be conservative since the formula has been derived for ships with high ice class. For ships without ice strengthening 25% to 50% lower collisions forces can be expected.

Similar empirical expressions for collision forces have been derived for sideway collisions by use of a number of detailed FEA, see Figure 10.

The variation of the load history of broadside collisions against rigid indenters differs from bow collisions. From Figure 10 it is seen that for a constant contact area the maximum load is the buckling load which occurs for small indentations at the beginning of the impact and that the impact velocity has very little effect on the crushing loads. In Pedersen (1998) the following global load formula is proposed for the crushing level P_{cside}:

$$P_{cside} = 263 F_s \left[1.0 + 0.88 (b/D)^{1.06}\right] * \left[L/300\right]^{2.20} [MN]$$

here F_s is a factor which accounts for the stiffening system (1.00 for longitudinal stiffening, 1.35 for transversely stiffening); b is the breadth of indenter [m]; D is the depth of the vessel [m], and L is the ship length [m].

Similar empirical expressions for impact loads for deck house collisions against the superstructures of the offshore installations are proposed in Pedersen (1998).

4.2 *Impact strength of offshore installation*

To evaluate the strength of the offshore installation it is normal to perform nonlinear finite element analysis of the crushing behavior of the different collision exposed structural members. A number of excellent finite element programs exist for such analyses of crushing loads as a function indentation or available crushing energy. See for example Amdahl & Holmås (2011); Dai et al. (2012), and Storheim & Amdahl (2014). Alternatively, the local capacity of tubular structures against ship impact loads can be determined by a simplified approach based on stepwise determination of plastic hinges, see Zhang et al. (2014).

5 PROBABILITY OF COLLAPSE

Based on the displacement distribution of the colliding vessels, Table 2, the associated calculated distributions of energy released for damage of the vessels and the empirical force-indentation curves for the relevant ship classes the distribution of impact forces can be established for the major structural elements of the offshore installation. Knowing the capacity of the platform then the annual probability of failure P_f can be calculated as the sum:

$$P_f = \sum_i^n P(R_i > R_o \mid collision) N_i(collision)$$

where R_i is the collision force distribution, R_o is the capacity of the struck member, and N_i is the annual

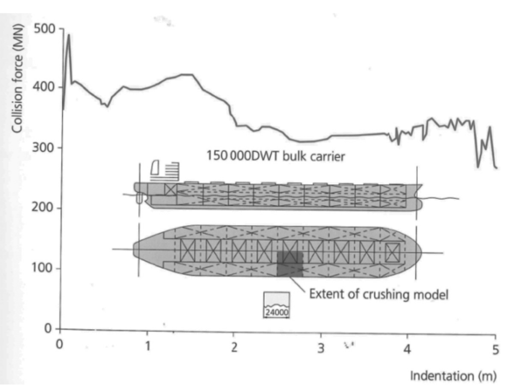

Figure 10. Finite element analysis for generation of empirical expressions for force versus energy for sideway collisions. Pedersen (1998).

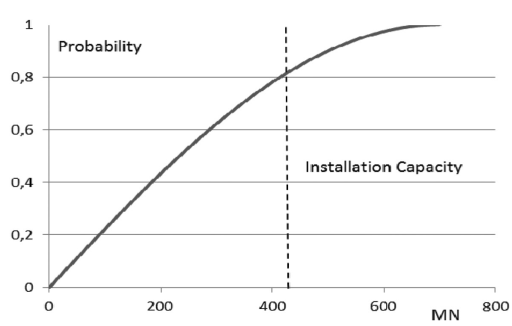

Figure 11. Collision force distribution for ships colliding on a specific offshore structural member with an indicated capacity.

frequency of collisions for ship class *i* against the considered structural member N_i is the probability for the event to take place. See Figure 11.

Approximate calculations such as those indicated above can also be used to determine the particulars of characteristic design ships determined such that the yearly frequency of structural failure of the most exposed structural elements is below a specified target. These design vessels can then be used for more detailed design analyses and studies of possibly improvement of the structural design.

6 CONCLUSION

The main objective of the procedures and the tools presented in this paper is to provide the designers with the maximum flexibility to design new cost-effective offshore structures for accidental ship collision loads based on performance standards for the structural requirements and the requirements to the navigational arrangements, instead of basing the design on the more traditional prescriptive rules or codes. The procedures are well suited for rapid prediction of the energy to be absorbed by crushing damage using Monte Carlo type prediction methods.

Based on available accident data for offshore structures it is found that one of the most the dominant risk contribution was from ship collisions caused by passing ships. The first part of the paper deals with procedures to estimate the probability of collisions with passing vessels for a given structure in a specific geographical area. With the direct calculation procedure presented in this first section, it is possible to introduce and quantify the effect of risk reduction methods such as new ship traffic lanes, new warning systems etc.

The second part of the paper deals with an important aspect which is quite often disregarded, i.e. the fraction of the initial ship kinetic energy which is available for structural damage of the offshore installation and/or the ship. It is most often too conservative to assume that all the kinetic energy of the colliding vessel has to be absorbed by damage (strain energy) in the involved structures. Non-central impacts and structural flexibility reduces the demands to structural crashworthiness.

Finally, the last section briefly discusses the effect of the relative strength of the involved structures and procedures to estimate probabilistic distributions of collision damages.

In summary, it can be concluded that at present basic mathematical tools are available for estimation of the risk associated with ship collisions for offshore installations such as fixed and floating offshore structures for hydrocarbon extraction, for offshore wind turbine farms, and for bridges spanning navigational channels. That is, it is demonstrated that for important offshore structures where risk acceptance criteria have been established then a rational risk assessment procedure can be developed and the calculated risks compared to the acceptance criteria by means of the general ALARP risk management approach.

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Ports

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The container terminal characteristics and customer satisfaction

V. Caldeirinha
Center of Management Studies, School of Economics and Management, Universidade de Lisboa, Portugal

J.A. Felício
School of Economics and Management, Universidade de Lisboa, Portugal

A. Dionísio
CEFAGE-UE, Universidade de Évora, Portugal

ABSTRACT: This paper evaluates the port user managers' perception of different operators on the influence of the port and container terminals characteristics on the customers' satisfaction. The structural equation modelling methodology is used to confirm the investigation model. The sample is composed by 151 valid responses, obtained from 12 Portuguese and Spanish container terminals. The results confirm the influence of the container terminal characteristics on the customer's satisfaction, which is an important contribution to the literature and port management.

1 INTRODUCTION

Containerisation has facilitated the globalization of maritime shipping services based on global logistic services (Cullinane et al., 2004). In the last years, competition between ports for hinterlands and for the main shipping trade routes has grown. Vessels have enlarged their size becoming more efficient. As a consequence, the shipping companies and logistic chain gained more bargaining power demanding higher port performance meeting customers' needs, better quality service and lower prices, becoming more disloyal (Wang and Cullinane, 2006).

The terminal choice is increasingly being made by logistic chain operators connected to specific shipping lines, based on the balance of price and quality service levels that can meet the requirements of complex systems of logistic chains (Bichou, 2007).

In such a competitive environment, the customer satisfaction is very important for terminal success and is determined by several complex factors, such as its physical and organizational ability, proximity to consumption and production, integration in logistic chains, maritime and inland accessibility, as well as the inland service and shipping networks connected (Tongzon and Heng, 2005).

This paper is justified by the insufficient knowledge of the relationship between port and container terminal characteristics and the container terminal users' satisfaction (Estache et al., 2005). There are a limited number of studies which use the structural equation model methodology and usually are based only on factors reduction without confirmatory analysis of structural model (Woo et al., 2011; Chang et al., 2008).

This study is based on port choice theory (Tongzon and Sawant, 2007; Tongzon, 2009), on port efficiency theory (Martinez-Budria et al., 1999; Gonzalez and Trujillo, 2008) and on port logistic performance theory (Bichou, 2007; Tongzon, 2002; Woo et al., 2011).

The objectives are to analyse the effect of port specialization, inland accessibility, logistic oriented management, and maritime accessibility in terminal customers' satisfaction.

The main questions addressed in this study are: Why do some container terminals have better performance than others? What are the most important characteristics of the container terminal for satisfaction? These questions were not fully answered in previous studies.

This study presents a very important contribution to the literature and terminal management by demonstrating the importance of container terminal customers' satisfaction based on the characteristics of container terminals.

This paper is organized as follows: after the introduction, and the theoretical background we present the methodology that consists of the research model and hypotheses, constructs and variables, and data collection and measurement. Following are the results and analysis, and discussion. Finally we present the conclusions, limitations and future research.

2 THEORETICAL BACKGROUND

Tongzon and Sawant (2007) and Tongzon (2009) analysed the factors of port performance seen on the side of the ship-owner, while choosing ports, especially container terminals, which leads us to one of the main theoretical branches around performance ports, port choice theory.

Martinez-Budria et al. (1999) and Gonzalez and Trujillo (2008), among many others, studied ports and container terminals in terms of the efficient frontier, looking for a way to measure the relative efficiency of each unit, terminal or port, considering input and output factors, which constitutes the third branch of theoretical port performance, the port efficiency theory.

Bichou (2007), Tongzon (2002) and Woo et al. (2011) analysed the determinants of performance of ports in the perspective of the ports in the global logistics chain, using several performance measures, in accordance with the multiple objectives of ports and terminals, which leads us to the fourth branch of theoretical the port performance, the port logistic performance theory.

2.1 *Port and terminal characteristics*

Chang et al. (2008) identified terminal service, shipping services, port dues, market oriented and infrastructure as performance factors. Location, physical characteristics, liner frequency, infrastructure, quay equipment, operating time and productivity and information system are important factor of terminal performance (Onut et al., 2011). Port activity is driven by liner services, location, accessibilities, information systems, produtivity, reputation and port community (Notteboom, 2011).

Port specialization is a performance factor mentioned by Trujillo and Tovar, 2007, Medda and Carbonaro, 2007, and it reflects the port evolution degree, from its industrial phase to a modern and commercial and intermodal port, and reflects the scale, learning and agglomeration effects of container and liner services with impact on performance.

The maritime accessibility is an important determinant of terminal performance, with diverse and frequent container maritime shipping services allowing a wider choice, greater flexibility and less transit times in the logistic chain, being associated to a higher port and terminal performance (Tongzon, 2002). Veldman and Buckmann (2003) explain the market shares of ports in northern Europe and its performance using factors such as liner shipping links. The maritime shipping services determine the success of the port based on its partnerships and the logistic networks in which are integrated (Tongzon and Heng, 2005). Maritime access depth is determinant of terminal performance, and allows serving bigger ships (Tongzon, 2002).

Turner, Windle and Dresner (2004) confirmed the importance of inland accessibility impact on performance and Gaur (2005) identified factors that affect the terminal performance such as connections with the hinterland.

As referred by Magala and Sammons (2008) the selection of a port has become more a function of the overall logistic chain performance that provides a full integrated service, which need a logistic oriented management. Marlow and Paixão (2003) referred to the port operator's ability to integrate their operations upstream or downstream the logistic chain, making use of value-added services, competing with other value-added chain systems.

The flexible organizational structure of the container terminal is important to provide an agile service that meets logistic customer's demands (Liu et al., 2009). Internal flexibility, agility and capability towards cooperation on logistic chain depend on the terminal organization system, type of management and on the terminal managers' training (Liu et al., 2009). Agile organizations include flexible and flattened organic (Liu et al., 2009). In the organizational integration context, the added value that ports can offer to logistic chains seems to be the key to succeed (Robinson, 2002).

Port integration in supply chains means a continuous terminal management improvement of lean elimination of redundancy, the reduction of handling costs, integrated information system, handling improvements and by offering value-added services to customers, specially contributing to ship-owner's satisfaction (Panayides and Song, 2009).

Onut et al. (2011) reported that the main performance criteria of the port include geographic location and physical characteristics. The location of the port is a key determinant of performance (Liu, 1995). Cheo (2007) refers to the importance of studying the influence of the port location where the port is located in its performance.

2.2 *Customers' satisfaction*

Brooks and Pallis (2013) report that port performance and competitiveness should be measured by efficiency and effectiveness. Report that performance is usually associated with operational efficiency, cargo physical quantities and efficiency in resource use (occupancy pier, revenue per ton, investment per ton and ship waiting time). However, the efficiency does not necessarily lead to greater competitiveness, which is also the result of effectiveness in delivering services desired by customers. Sometimes the efficiency of the terminal may even be contradictory to the effectiveness of the service satisfaction, being necessary balance (Brooks & Pallis, 2013). The customers and stakeholders perception measurement is very important for terminal management and investment plans to meet supply chain needs, but terminal users may rate satisfaction differently (Brooks & Pallis, 2013).

The fulfilment of container terminal customers' needs and their satisfaction, goes beyond the efficiency that was traditionally been considered in the perspective of infrastructures, meaning that the creation of value has changed from the simple efficient container terminal operation to an effective integrated service in supply chains (Robinson, 2002; Bichou, 2007).

3 METHODOLOGY

3.1 *Research model and hypothesis*

The research model is based on the definition of a global conceptual and holistic model that includes the port and container terminal characteristics and their relation with the terminal customer's satisfaction (Fig. 1).

Based on the theoretical background, the following assumptions are settled:

- Hypothesis 1a: Port specialization is an important characteristic of the port and container terminal;
- Hypothesis 1b: Port and terminal inland accessibility is an important characteristic of the port and container terminal;
- Hypothesis 1c: Terminal maritime accessibility is an important characteristic of the port and container terminal;
- Hypothesis 1d: Logistic oriented management of the terminal is an important characteristic of the port and container terminal;
- Hypothesis 2: Container terminal customer's satisfaction is strongly influenced by port and terminal characteristics.

3.2 *Constructs and variables*

Based on literature and on the results of the exploratory analysis made to data resulting from the questionnaire, the port and terminals characteristics is explained by four constructs: (i) Port specialization, (ii) Inland accessibility, (iii) Maritime accessibility, and (iv) Logistic oriented management (Table 1).

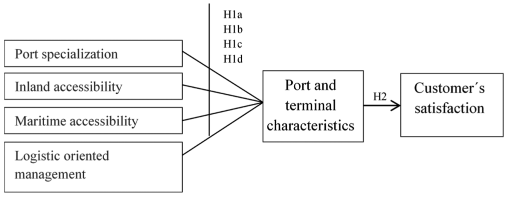

Figure 1. Research model.

3.2.1 *Data collection and measurement*

Data were collected based on a survey sent to the main Portugal and Spain container terminal's users. A question was addressed to each variable, concerning the evaluation of terminal characteristic and the customers' satisfaction level, using a 7-point Likert scale. The questionnaire was submitted to 1139 user managers from companies operating in the selected terminals, with a 151 valid answers (Table 2).

The component of the survey relating to the construct Costumer's satisfaction was based on the question "Do you agree that the container terminal satisfies the customer?" after identifying each type of customer. The remaining variables were based on the general question "Do you agrees that the container terminal is good in the variable x?".

3.3 *Statistical instruments*

The structural equation model is a linear model that sets a relation between observed and latent variables and between endogenous and exogenous variables, whether latent or observed. It is divided in two sub-models: the measurement model and the structural one.

The measurement model defines how the latent variables are operationalized by the observed ones, including exogenous variables and endogenous ones. The measurement model of endogenous variables is defined as follows (Bollen, 1989):

$$y = \Lambda y \ \eta + \varepsilon \tag{1}$$

where, y is the vector (p × 1) of observed dependent p variables, Λy is the factor weight matrix (p × r) of η in y, η is the vector (r × 1) of dependent latent r variables and ε is the measurement errors vector (p × 1) of y.

The measurement model of exogenous variables is defined by:

$$x = \Lambda x \ \xi + \delta \tag{2}$$

where, x is the vector (q × 1) of independent observed p variables, Λx is the factor weight matrix (q × s) of ξ in x, ξ is the vector (s × 1) of independent latent's variables and δ is the measurement errors vector (q × 1) of x. The structural model defines the causal relations between latent variables, which can be defined by:

$$\eta = B\eta + \Gamma\xi + \varsigma \tag{3}$$

Table 1. Constructs and variables.

	Variables	Authors
Customer's satisfaction	Shipper/logistic chain operator satisfaction	Robinson, 2002; Liu et al., 2009
	Shipowner's satisfaction	Liu et al., 2009
	Shipping agent's and freight forwarder's satisfaction	Liu et al., 2009; Magala and Sammons, 2008
	Satisfaction with productivity	Onut et al., 2011; Talley, 2006
Port specialization	Port specialization in container	Trujillo and Tovar, 2007; Medda and Carbonaro, 2007; Onut et al., 2011; Tongzon, 2002
	Frequency of port Short Sea Shipping (SSS)/feeder services	Veldman and Buckmann, 2003; Hung et al., 2010
Inland accessibility	Railway accessibilities	Juang and Roe, 2010; Onut et al., 2011
	Road accessibilities	Juang and Roe, 2010; Tongzon, 2002, Wiegmans, 2003; Turner, Windle and Dresner, 2004; Gaur, 2005
	Terminal size	Hung et al., 2010; Wu et al., 2010
	Terminal layout	Magala and Sammons, 2008
	Railway connections to inland terminals	Juang and Roe, 2010; Chang et al., 2008; Tongzon and Sawant, 2007; Panayedes and Song, 2009
	Logistic areas near the port	Magala and Sammons, 2008; Wu et al., 2010
Maritime accessibility	Quay water depth	Wang and Cullinane, 2006
	Maritime access	Tongzon, 2002; Wang and Cullinane, 2006, Gaur, 2005; Turner et al., 2004
	Vessels size	Turner et al., 2004; Hung et al., 2010
	TOP10 liner services frequency	Song e Yeo, 2004; Tongzon 2002; Tongzon and Heng, 2005
Logistic oriented management	Terminal brand	Juang and Roe, 2010; Onut et al., 2011; Chang et al., 2008; Cheo, 2007; Pando et al., 2005; Pardali and Kounoupas, 2007; Cahoon and Hecker, 2007
	Type of terminal manager	Liu et al., 2009
	Overall services quality	Woo et al., 2011; Juang and Roe, 2010; Hung et al., 2010; Liu et al., 2009
	Customer oriented terminal	Juang and Roe, 2010; Onut et al., 2011; Carbone and De Martino, 2003; Liu et al., 2009
	Terminal organization	Bicou and Gray, 2004; Robinson, 2002; Liu et al., 2009
	Information system	Carbone and De Martino, 2003; Panayedes and Song, 2009; Cachon and Fisher, 2000; Zhao et al., 2002; Liu et al., 2009
	Agility face to changes	Woo et al., 2011; Onut et al., 2011; Liu et al., 2009
	Operational and commercial flexibility	Liu et al., 2009; Notteboom and Winkelmans, 2004
	Terminal reliability	Chang et al., 2008; Tongzon et al., 2009
	Berth productivity	Onut et al., 2011; Tongzon et al., 2009; Juang and Roe, 2010; Liu et al., 2009
	Vessels waiting time	Onut et al., 2011
	Terminal integration in logistic chains	Juang and Roe, 2010; Tongzon and Heng, 2005; Hung et al., 2010; Panayedes and Song, 2009; Marlow and Paixão, 2003; Liu et al., 2009
	Terminal Handling charge	Onut et al., 2011; Song e Yeo, 2006; Tongzon et al., 2009; Juang and Roe, 2010

where, B is the matrix $(r \times r)$ of η coefficients of the structural model with $\beta ii = 0$, Γ is the matrix $(r \times s)$ the x coefficients in the structural model, ς is the vector $(r \times 1)$ of r model residuals.

The structural equation model can be exploratory or confirmatory regarding the analysis of latent variables or factors, aiming to determine the latent variables or to confirm their existence and relationships with the observed ones. This methodology was used to confirm the measurement model of latent factors explaining the container terminal performance, as well as the latent variables of performance by using AMOS18 software.

Table 2. Sample definition.

Country	Sent questionnaires	Sample	%	Port	Terminal	Sample *per* terminal
Portugal	573	111	19,4	Figueira	Figueira	4
				Leixões	TCL	24
				Lisboa	Liscont	34
					TCSA	11
					TML	4
				Setúbal	Sadoport	16
				Sines	XXI	18
Spain	566	40	7,1	Algeciras	APM Algeciras	6
				Barcelona	TCB	8
				Bilbao	NCTB	9
				Tarragona	DPWT	8
				Valencia	Noatum	9
Total	1139	151	13,3	10 ports	12 terminals	151

4 RESULTS AND ANALYSIS

4.1 *Data analysis*

By using the structural equation model methodology, the confirmatory analysis of the research and hypothesis model was performed. The collected variables were used to determine the model latent variables. In the questionnaire, user managers were asked to choose, on the scale between total agreement (7) and total disagreement (1) regarding the high customer's satisfaction of a specific terminal previously identified. It also asked the scale of appreciation of each of the factors of port and terminal characterization, qualified in a positive way in the question with customer's satisfaction. Average high results to customer's satisfaction (between 4.89 and 4.97) and important results to characterization factors (between 4,03 and 5.23) were obtained, which confirmed the potential importance of these factors to terminal performance in the opinion of user managers who answered the questionnaire (Table 3).

4.2 *Structural equation results*

Based on the hypotheses and after tests, it was found that the initial constructs have an high adequate fit. The model latent exogenous variables, with internal consistency, reliability validity and unidimensionality validity, were determined (Hair et al., 1998; Tabachnick & Fidell, 2001).

4.3 *Measurement model*

First, it was developed the measurement model and significant coefficients of latent variables relations with the observed ones (>0.55) were obtained (Table 4). The model convergence validity (Anderson et al., 1987; Garver and Mantzer, 1999) was confirmed, which guarantees the model suitability to the input data. The face validity of latent variables was also confirmed, due to the fact that each determined latent variable showed consistency with concepts and definitions found in literature and in the theoretical model. The model aims to measure distinct and robust latent variables. The explained variance ($R2 > 0.4$) of the model latent variables is high, which indicates the model robustness.

As Table 5 shows, the correlation between latent variables is inferior to 0.85 and inferior to square root values of Average Variance Extracted (AVE) of the latent variables, diagonally presented in the table, indicating that the latent variable are internally consistent and distinct from each other. The AVE values of first level latent variables are greater than 0.6. In addition, these results indicate the robustness of the latent variables used in the structural equation model, demonstrating the discriminant validity of the model (Fornell and Larcker, 1981; Kline, 2005).

The results also confirm the unidimensionality of the structural equation model (Hair et al., 1998; Tabachnick and Fidell, 2001) with the following indicators of Goodness-of-fit (GoF) of the measurement model $\chi 2$ 808.959; $\chi 2/df$ 2.033; IFI: 0.902 (>0.9); CFI: 0.901 (>0.9); RMSEA: 0.083 (<0.1) showing a good adjustment of the latent variables measurement model.

The resulting measurement model confirmed the existence of the dependent latent variable Customer's satisfaction also confirming the existence of four exogenous latent variables or independent/

Table 3. Descriptive statistics.

Construct	Variable	Min	Max	Average	Std. deviation	Skewness	Kurtosis
Customer's satisfaction	Shipper/logistic chain operator's satisfaction	2	7	4.95	1.145	–0.502	–0.422
	Shipowner's satisfaction	1	7	4.96	1.311	–0.592	–0.137
	Shipping agent and freight forwarder's satisfaction	2	7	4.97	1.180	–0.601	–0.196
	Satisfaction with productivity	1	7	4,89	1,490	–0.625	–0.101
Port specialization	Port specialization in containers handling	1	7	5.12	1.336	–0.799	0.485
	Frequency of maritime SSS/ feeder services of the port	1	7	4.81	1.392	–0.639	–0.073
Inland accessibility	Railway accessibilities	1	7	4.44	1.668	–0.215	–0.903
	Road accessibilities	1	7	4.97	1.655	–0.573	–0.621
	Terminal size	2	7	4.64	1.463	–0.162	–0.901
	Terminal layout	2	7	4.94	1.218	–0.423	–0.413
	Railway connections to inland terminals	1	7	4.20	1.755	–0.256	–0.863
	Logistic areas near the port	1	7	4.21	1.761	–0.120	–0.986
Maritime accessibility	Terminal quay depth	1	7	4.48	1.673	–0.244	–0.962
	Maritime access	1	7	4.57	1.749	–0.477	–0.799
	Vessels size	1	7	4.13	1.682	–0.107	–0.875
	Frequency of top 10 liner services shipping companies	1	7	4.03	1.593	–0.175	–0.727
Logistic oriented management	Terminal brand	1	7	5.23	1.239	–0.992	1.138
	Type of terminal manager	1	7	5.18	1.410	–0.930	0.721
	Overall service quality	1	7	4.87	1.235	–0.425	–0.069
	Customer oriented terminal	1	7	4.63	1.472	–0.428	–0.631
	Terminal organization	1	7	5.18	1.195	–0.779	0.474
	Information systems	1	7	5.10	1.305	–0.715	0.582
	Agility facing changes	1	7	5.06	1.358	–0.854	0.686
	Operational and commercial flexibility	1	7	5.02	1.324	–0.578	0.141
	Terminal reliability	1	7	5.19	1.319	–0.719	0.403
	Berth produtivity	1	7	5.17	1.330	–0.958	0.891
	Vessels waiting time	1	7	5.23	1.342	–0.755	0.286
	Terminal integration in logistic chains	1	7	4.54	1.427	–0.284	–0.213
	Terminal handling charge	1	7	4.15	1.482	–0.079	–0.630

explanatory factors of performance: Port specialization, Inland accessibility, Maritime accessibility and Logistic oriented management.

This structural model result allows the confirmation of the theoretical research model considering Iberian Peninsula terminal users' perception. In other words, the container terminal customer's satisfaction depends indirectly on the level of port specialization in container and on the frequency of short sea and feeder lines, inland accessibility, terminal infrastructure, logistic areas nearby, connection to inland logistic areas, brand, type of manager and terminal organization, and on terminal service quality and logistic integration, i.e. orientation towards the logistic chains' needs, reliability, flexibility and agility, suitable information system, vessels operations duration, and waiting time and handling rates.

4.4 *Structural model*

Second, it was developed the structural model with causal relations between the latent variables was developed, with a second level latent regarding Port and terminal characteristics (Fig. 2). The results of the structural model also point out the fulfilment of the unidimensionality criteria (Hair et al., 1998; Tabachnick & Fidell, 2001), with the

Table 4. Model estimated coefficients.

		Estim.	S.E.	β	C.R.	P
Quay water depth	Maritime accessibility	1.00		0.48		
Maritime access	Maritime accessibility	1.13	0.09	0.75	13.23	***
Vessels size	Maritime accessibility	1.36	0.14	0.95	9.98	***
TOP 10 liner services frequency	Maritime accessibility	1.10	0.12	0.80	8.99	***
Type of terminal manager	Logistic oriented management	1.00		0.76		
Terminal brand	Logistic oriented management	0.99	0.09	0.86	11.54	***
Overall services quality	Logistic oriented management	1.03	0.09	0.89	11.88	***
Costumer oriented terminal	Logistic oriented management	1.05	0.11	0.77	10.04	***
Terminal organization	Logistic oriented management	0.79	0.06	0.71	13.10	***
Information system	Logistic oriented management	0.91	0.09	0.75	9.73	***
Agility face to changes	Logistic oriented management	1.04	0.10	0.82	10.88	***
Operational and commercial flexibility	Logistic oriented management	1.05	0.09	0.85	11.29	***
Terminal reliability	Logistic oriented management	1.10	0.09	0.90	12.07	***
Berth produtivity	Logistic oriented management	1.09	0.09	0.88	11.84	***
Vessels waiting time	Logistic oriented management	1.04	0.09	0.83	11.02	***
Terminal integration in logistic chains	Logistic oriented management	0.87	0.11	0.66	8.33	***
Terminal handling charge	Logistic oriented management	0.87	0.11	0.63	8.03	***
Port specialization	Port and terminal characteristics	1.00		0.64		
Inland infrastructure	Port and terminal characteristics	1.17	0.22	0.70	5.22	***
Maritime shipping service	Port and terminal characteristics	0.92	0.19	0.57	4.74	***
Organization and logistic integration	Port and terminal characteristics	1.39	0.23	0.92	6.11	***
Costumer satisfation	Port and terminal characteristics	1.19	0.19	0.84	6.21	***
Port specialization in container	Port specialization	1.00		0.83		
Frequency of port SSS/feeder services	Port specialization	0.81	0.15	0.64	5.43	***
Shipping agent's and freight forwarder's satisfaction	Costumer satisfation	1.00		0.86		
Shipper/logistic chain operator satisfaction	Costumer satisfation	0.98	0.07	0.87	14.27	***
Shipowner's satisfaction	Costumer satisfation	1.11	0.08	0.86	13.42	***
Satisfaction with productivity	Costumer satisfation	1.24	0.10	0.84	12.80	***
Road accessibilities	Inland accessibility	1.00		0.72		
Railway accessibilities	Inland accessibility	1.15	0.12	0.82	9.50	***
Terminal size	Inland accessibility	0.83	0.11	0.67	7.61	***
Terminal layout	Inland accessibility	0.72	0.09	0.70	7.91	***
Railway connections to inland terminals	Inland accessibility	1.04	0.13	0.71	7.96	***
Logistic areas near the port	Inland accessibility	1.18	0.13	0.80	9.08	***

Table 5. Consistency of the latent variables, measurement model.

Latent	Var.	AVE	1 (2nd level)	2	3	4	5	6
Port and terminal characteristics (2nd level)	1	0.64	0.80					
Port specialization	2	0.60	0.63	0.78				
Maritime shipping service	3	0.76	0.56	0.57	0.87			
Organization and logistic integration	4	0.75	0.80	0.60	0.53	0.87		
Inland infrastructures	5	0.67	0.69	0.44	0.39	0.66	0.82	
Terminal costumer's satisfaction	6	0.84	0.79	0.53	0.46	0.80	0.58	0.92

Note: AVE (average variance extracted) square root in diagonal.

following indicators of Goodness-of-fit (GoF), $\chi 2$ 883.657; $\chi 2$/df 2.441; IFI: 0.868 (>0.9); CFI: 0.867 (>0.9); RMSEA: 0.098 (<0.1), harmed by the reduced sample size. The relations between the second level latent variable Port and terminal characteristics and the first level exogenous latent variables of the reflexive model means that the latter are the reflex of a superior variable which is confirmed by high coefficients in relations (>0.5).

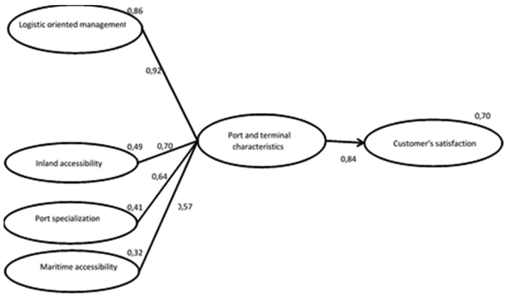

Figure 2. Structural model.
Note: β values of variable relations and R2 values (β × β) of dependent variables are in evidence. All β values are significant at 0,001 (two-tailed).

5 DISCUSSION

The obtained results allow us to consider as pertinent the research model as well as the holistic vision about port and container terminal characteristics to have influence on terminal customer's satisfaction with a significant 70% explanation degree of the respective variance.

The second level latent variable Port and terminal characteristics is reflected in the first level latent variables, explaining in 86% the Logistic oriented management, in 49% in inland accessibility, in 41% in port specialization and in 32% Maritime accessibility (Fig. 2). In turn, each of these first level latent variables explain its observed variables in high level.

The existence of various consistent latent variables regarding the Port and terminal characteristics was verified. The results evidence the existence of a latent characteristic Port specialization (AVE = 0.60; β = 0.64), which is reflected in the observed variables Container Port specialization (β = 0.83) and Frequency of maritime shipping services of short-sea-shipping and feeder (β = 0.64), which demonstrates the importance of specialization as a model factor, namely the containerization rate, already referred by Trujillo and Tovar, 2007, Medda and Carbonaro, 2007.

This demonstrates that terminals located in ports with higher container specialization usually have higher customer's satisfaction levels when using the respective infrastructures. A specialized port can usually achieve high performance levels due to the port overall services and infrastructures' suitability to container handling and operations. The importance of port specialization in liner services was also demonstrated, because the high frequency of container liner services at a port allows cargo owners to have a wider choice, more flexibility and less "transit times", which is associated to a higher port specialization in container handling (Tongzon, 2002). Hypothesis 1a is not rejected: Port specialization is an important characteristic of the port and container terminal.

The results also indicate the existence of the latent characteristic Inland accessibility (AVE = 0.67; β = 0.70) that is reflected in the observed variables Railway accessibilities (β = 0.82), Road accessibilities (β = 0.72), Terminal width (β = 0.67), Terminal layout (β = 0.70), Railway connections to inland terminals (β = 0.71) and Logistic areas near the port (β = 0.80), showing the importance of inland infrastructures to customer's satisfaction, especially inland accessibilities, to enlarge the hinterland and contribute to maximize terminal investments.

Therefore, the conclusions of Turner, Windle and Dresner (2004) and Gaur (2005) about the impact of inland accessibilities on performance were confirmed. The hinterland accessibilities allow terminal expansion beyond the seaport limits, therefore enlarging its influence area to inland terminals, connected by rail. Inland infrastructures also include infrastructure quality and the terminal itself, with all its characteristics, equipment and layout, as well as the existence of logistic areas nearby, as being determinant to the customer's satisfaction. These findings support the conclusions of various authors such as Juang and Roe (2010), Onut et al. (2011), Hung et al. (2010) and Wu et al. (2010). Hypothesis 1b is not rejected: Inland accessibility is an important characteristic of the port and container terminal.

The results identify the existence of a latent variable characteristic Maritime accessibility (AVE = 0.76; β = 0.57), which is reflected in the observed variables Terminal quay depth (β = 0.69), Maritime access (β = 0.75), Vessels' size (β = 0.95) and Frequency of liner servicer of the Top 10 worldwide shipping companies (β = 0.80). These results are consistent with those of Tongzon (2002) about the importance of liner services, especially those of worldwide shipping companies, in shippers' terminal selection process, leading to a higher customer's satisfaction. And confirms the importance of partnerships with logistic networks (Tongzon and Heng, 2005) and of maritime access depth allowing to serve bigger ships as determinants of performance (Tongzon, 2003).

As with previous cases, hypothesis 1c is not rejected: Maritime accessibility is an important characteristic of the port and container terminal.

The results also show that there is a latent variable characteristic Logistic oriented management (AVE = 0.75; β = 0.92), the most important variable in the model for satisfaction, wich is reflected on the observed variables Terminal brand (β = 0.86), Type of terminal manager (β = 0.76), Overall service quality (β = 0.89), Customer oriented terminal (β = 0.77), Terminal organization (β = 0.71), Information system (β = 0.75), Agility face to changes (β = 0.82), Commercial and operational flexibility (β = 0.71), Terminal reliability (β = 0.90), Berth occupancy (β = 0.88), Vessels' waiting time (β = 0.83), Terminal integration in logistic chains (β = 0.66) and Terminal handling charge (β = 0.63). This demonstrates the importance of ports, while integrated in the logistic chain, to overall performance (Robinson, 2002). Logistic integration of ports requires a strong orientation towards the customer, compatible information systems, agility, flexibility, reliability, price and service quality (Notteboom and Winkelmans, 2004).

The results confirm Robinson (2002) findings about the port selection being made in the context of the supply chain, which demands an enlarged vision of the port and terminal. It is confirmed that orientation towards the customer is very important to their satisfaction by allowing a fast adaptation to market changes in cooperation with the customer.

The importance of the information systems is confirmed as it allows information sharing, leading to high levels of the container terminal's integration in the supply chain.

Also, the importance of the type of manager, oriented towards the customer and the logistic chain, is confirmed, as well as the type of organization that determines the terminal agility while answering to logistic network demands (Liu et al., 2009). Therefore, Hypothesis 1d is not rejected: The Logistic oriented management is an important characteristic of the port and of the container terminal.

The results allow considering as pertinent the hypothesis that the port and terminal characteristics influence terminal customer's satisfaction (β = 0.84, R2 = 0.70), not rejecting the basic hypothesis of the research model. The container terminal customer's satisfaction is indirectly influenced by inland accessibility, port specialization, logistic oriented management and maritime accessibility. Hypothesis 2 is not rejected: Container terminal customer's satisfaction is strongly influenced by the port and terminal characteristics.

6 CONCLUSIONS, LIMITATIONS AND FUTURE RESEARCH

The present study allowed the development of an explanatory overall holistic model of port customer's satisfaction, based on the port and on the terminal characteristics.

First, we found that if it is important to study terminal efficiency using quantitative and physical variables, it is also increasingly relevant to understand container terminal customers' satisfaction, as a qualitative perception from terminal users. The main terminal characteristic influencing users' satisfaction is the terminal logistic oriented management. This characteristic can be not relevant influencing terminal efficiency or productivity, but it is one of the most important factors for customers' satisfaction. The terminal should be a part of global logistic chain, and cannot work for itself.

Second, the inland and maritime accessibilities are not as important as logistic oriented management, but are determinant factors of the terminal characteristics to customers' satisfaction. Once again the logistic chain point of view, looking for adequate terminal links to hinterland and foreland.

Third, users are more satisfied with terminals inside container specialized ports than in other ports, because it is very important to them to have concentrated ports, with accessibilities, services and equipment specialized in containers, to set their logistic chain to one specialized port, with the possibility to choose between several terminals.

Finally, it was been found the existence of a second-level latent variable, Port and terminal characteristic that explains the four main latent factors characterizing the port and terminal. This means that there is a strong correlation between the main characteristics of the port and terminal. Ports specialized in containers and liner shipping have better inland accessibility, have a better maritime accessibility, and have a management more oriented to logistics. In theory, it has been found that these different characteristics reflect a higher latent variable.

The study contributes to a better knowledge of ports and container terminals for having succeeded to concentrate in only one model the various elements from previous studies. This research model contributes to a better understanding of the fact that successful container terminals with high customer's satisfaction must necessarily have an adequate organization and management, high quality services, orientation towards the customer, in order to meet the logistic chain demands, in which the terminal is integrated, in terms of agility, flexibility, reliability, information systems, prices, berth occupancy and vessels waiting time.

One limitation of the present study is the sample size considering the number of terminals observed, although being representative of the population of the Iberian Peninsula ports.

An interesting future research work would be applying this model to other worldwide port terminals, testing validity in an enlarged geographical context.

In future studies it should be developed the analysis of the customers' satisfaction, trying to detail the different types of satisfaction and the different type of users with cargo, forland, geographic and industry segments.

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Performance evaluation using data envelopment analysis: The case of Portuguese general cargo terminals

J.F.C. Grilo
Instituto Superior Técnico, Universidade de Lisboa, Portugal

J.C.Q. Dias
Instituto Superior de Engenharia de Lisboa (ISEL) and Centre for Marine Technology and Engineering (CENTEC), Instituto Superior Técnico, Universidade de Lisboa, Portugal

ABSTRACT: This paper aims to assess the performance of the main Portuguese terminals that handle general cargo. The method adopted for the performance evaluation is the Data Envelopment Analysis (DEA) that compares the terminals between each other by benchmarking and determines the existent inefficiencies of the system. It was chosen to optimize the resources (infrastructures, equipment etc) in relation to the fixed yearly values of cargo throughput of each terminal. The variables were selected with the aid of the Compensatory Method of Single Standardization, which determines the variables to be used by an efficiency index. The results demonstrate that the terminals have different performance levels and different patterns of efficiency. Furthermore the most efficient terminals are identified for this type of cargo, on the Portuguese ports, and issues are identified which can improve the overall efficiency.

1 INTRODUCTION

Benchmarking is a popular instrument that is globally accepted as a tool to improve the performance and competitiveness of business organizations. The scope of applications varies from large corporations to small business companies, public and semi-public sectors and covers several types of industries (Ball, 2000; Davis, 1998; Jones, 1999; McAdam & Kelly, 2002). Some authors denote benchmarking as a management tool that can be defined as the systematic process of searching for best practices, efficient and innovative ideas that lead to continuous improvement (McNair & Leibfried, 1992; Spendolini, 1992; Bhutta & Faizul, 1999; Bogan & Callahan, 2001; Deros, 2006).

The competitiveness in the international market implies that each nation has good relations with other countries, skilled people, and appropriate infrastructures to meet their needs. Economic globalization has caused changes in the market, from production to consumption, inducing forced competitiveness throughout the supply chain.

The planning and management of all product movement, measuring costs, has become an essential condition in the dispute for the consumer market. Thus, cost reduction has become indispensable to the success of corporations in the global market condition. Cost reduction can be achieved by minimizing inefficiencies and by making a better use of the infrastructures. By optimizing the whole supply chain the country will be ranked on the international stage with a higher level of competitiveness. The transportation system, together with the correlative infrastructures, has proven to be crucial for satisfactory performance and market growth of the country. Ports are links of the transportation system and key elements for the interconnection with other nations. They are considered privileged instruments of the external commerce since ships are the mean of transportation that moves largest amounts of cargo per trip, UNCTAD (1992). International trade is closely connected to seaports, since almost all goods moving around the world are transported on ships and managed by ports.

Portugal presents the maritime mode of transportation as the mean of transportation with the highest values of imported cargo. By presenting features that highlight the country's maritime sector as the 943 km of border with the Atlantic Ocean and due to the economies of scale and low costs, Portugal can also be considered a main entrance and exit of goods by shipment in Europe. But unfortunately, according to the location of European centers of production and consumption, Portuguese ports are clearly peripheral as shown in Figure 1.

From the ITMMA Report, 2009 (p. 57), it is concluded that: *"A large number of manufacturing companies have set up business in lower cost regions in*

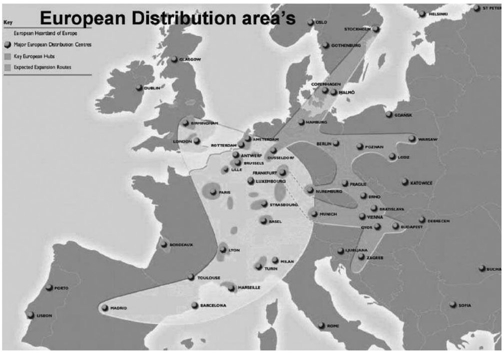

Figure 1. Location of Portugal outside *Blue Banana*. Source: ITMMA Report, 2009, (p. 57).

Eastern Europe. This development has led to larger bi-directional East-West flow within the European Union of raw materials and consumer products. The traditional 'blue banana' is approaching the shape of a boomerang as a result of extensions to central and east Europe and significant investments in the Mediterranean (Spain in particular). The expansion of the 'blue banana' also goes hand in hand with the development of trade flows in the Baltic area, Central Europe and the Latin arc (stretching along the coastline from southern Spain to northern Italy)".

In these conditions the limitations of the Portuguese port sector in response to the European production and consumption are good reasons for its further study, namely regarding its performance and efficiency. There are several recent studies regarding containerized cargo (Dias et al., 2009; Dias et al., 2012) but the same is not true when it comes to general cargo and bulk cargoes handling.

The analysis of seaports that handle break bulk cargo, commonly known as general cargo, is vital to the overall development of the sector. Therefore, inefficiency or gaps presented in the handling of the cargo could become a barrier to the development of the port, on national level.

The use of the DEA method to analyze and evaluate port terminals is due to the different possibilities of analyzing the data that the method provides and performing a comparative analysis of efficiency of a set of units contained in the same sector of activity.

2 STATE OF THE ART

2.1 *Seaport logistics*

A seaport, being a sub-system of the total transportation network and a venue of other means of transport, is essentially an economic infrastructure that serves to handle domestic and overseas cargoes. The increase of transportation distances which is caused by economic globalization implies, usually, the use of more complex transportation networks, modes and platforms. The loading, unloading, transshipping and preparation of cargoes are expensive and time-consuming operations, especially if they depend on transport systems which are not prepared for multimodal operations, Janelle & Beuthe (1997). The internationalization of transportation provides significance to logistical requirements for intermodal transport of passenger and freight (Janelle & Beuthe, 1997; Rodrigue, 1999). The replacement of the traditional heterogeneous maritime cargoes by homogeneous containers and the adoption of the container concept have created a revolution in ports which allowed maritime shipping to benefit from economies of scale not only in cargo handling but also in ship size, Cullinane & Khanna (2000).

Although the container is the most important development in the improvement of the multimodal concept of transportation in general and in seaports in particular, Johnston & Marshall (1993), there is still a lot of cargo, such as oversized and heavy weight equipment, which has to be shipped in break bulk. There is a lot of research done about containerized cargo but not so much about break bulk or the so called general cargo. The large economic growth of countries outside Europe, namely in East Asia (Ha, 2003; Yap et al., 2006), justifies the growing demand of cargo movements, Janelle & Beuthe (1997). According to Dowd & Leschine (1990) seaport terminals are the physical connection between maritime transport, land transport and several components of the freight transport network. The terminal is therefore an important part of the chain, any increase in efficiency will contribute to the competiveness of the full network (Mendonça & Dias, 2007; Dias et al., 2010; Yeo et al., 2010). Turner et al. (2004) claims that the magnitude of the seaport infrastructure and connections to the predecessor and successor in the supply chain, such as being linked to railways, contributes to the increase of the productivity of ports.

2.2 *Performance evaluation*

Performance of a system can be defined as the result of the combination of its elements. To evaluate a system in terms of its performance it is necessary to study the characteristics of the system and define the methods to be used. The performance evaluation of a company or organization is the way of measuring, based on one or more indicators, if the system is functioning effectively. By this the companies can assess if the adopted measures are having the desired effect and determine which measures can be used to further improve the process. The basic objectives of a performance analysis are to improve the organizational management and control. These processes look for a balance of the system's components, as for example managing the capacity in order to reduce waste. To analyze a seaport's performance it is necessary to define the correct parameters that can monitor the performance and indicate methods to improve it. Standards have to be defined to allow a performance to be measured. This performance has to be observed from the perspective of the seaport administration and of its users.

Antão et al. (2005) says that benchmarking is more precise if the parameters defined for the seaport comparison are grouped in a selective way, e.g., according to specific characteristics. Studies that evaluate seaport performance intend to define and specify the various factors that can influence this performance and also its efficiency.

A seaport performance is affected by numerous factors. Some of these factors are out of control of the authorities, as the economic level of the sector, the geographic location of the port, or the frequency of ships in transit, Tongzon (1995). There are at least two factors that ports can control directly, depending on their role on the waterfront: terminal efficiency and harbor fees. Tongzon (1995) supports the theory that a terminal's efficiency is an essential component to any waterfront reform aimed at improving the port's performance. This indicates that the efficiency of the terminals has a strong influence to all factors that determine a seaports performance, ensuring that the increase in efficiency of a terminal is a high priority in a general reform of a port.

3 DATA ENVELOPMENT ANALYSIS

Data Envelopment Analysis—DEA was developed by Charnes et al. (1978). It is a linear programming based method defined to measure comparative efficiencies of entities called *Decision Making Units* (DMUs). These units use the same resources (inputs) and generate the same products (outputs). This technique results in a relative efficiency that counts the ratio between virtual inputs and outputs, in accordance with Equation (1) below, where y_{rj} represents an output r of the unit j. x_{ij} represents an input i of the unit j. v_i and u_r represent, respectively, the weights of each input i and each output r.

$$Efficiency_j = \frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} \quad (1)$$

In this paper we assume the concept of efficiency as the ability to do more and better with less means (more outputs with fewer inputs).

DEA is intended to measure and find inefficiency between DMUs. The DMUs adopted should have the same use of inputs and outputs, varying only in intensity. This collection should be homogeneous, e.g., should realize the same tasks with the same goals, work under the same market conditions and have autonomy of making decisions. The selection of the relevant variables (inputs and outputs), for the evaluation of the relative efficiency of the DMUs, should be done according to the problem being analyzed, because the results of the analysis depend on the inputs and outputs selected.

There are two classic DEA models: CCR and BCC. The CCR model (also known as CRS or constant returns to scale) uses constant returns to scale as an hypothesis. The DEA CCR model maximizes the ratio between the linear combination of outputs and the linear combination of inputs, with the restriction that for any DMU this ratio cannot be greater than 1. The BCC model, Banker et al. (1984), or VRS (variable returns to scale), considers production efficiency cases with variable scale and does not assume proportionality between inputs and outputs.

From a non-mathematical point of view, BCC model indicates an efficient DMU as the one that makes better use of the available inputs, within the scale it operates. The CCR model shows an efficient DMU when the unit presents the best ratio of outputs in relation to inputs, e.g., makes better use of inputs without considering the scale of operation of the DMU.

These models can be oriented to optimize inputs, outputs or both. This orientation should be defined according the goals and conditions of the system to be analyzed. This method indicates, for each inefficient unit, subgroups of efficient units as a reference set.

In Figure 2, model CCR is illustrated. "A", "B", "C" and "D" are the DMUs analyzed. The DMU "B", because it is on the frontier, is considered efficient. The arrows indicate the projection of each inefficient DMU on the frontier through the reduction of resources (inputs), "AK", "CM" and "DO". This is required to make the DMU efficient.

Figure 3 shows the BCC model, oriented to inputs, in a graphical form. "A", "B", "C", "D", "E", "F" and "G" are the analyzed DMUs. The DMUs "A", "B", "C" and "D", are on the efficiency frontier and so considered efficient. DMUs "E", "F" and "G" will need to reduce their inputs to be considered efficient.

For this project the CCR model was first used, and then the BCC model, both input-oriented. This

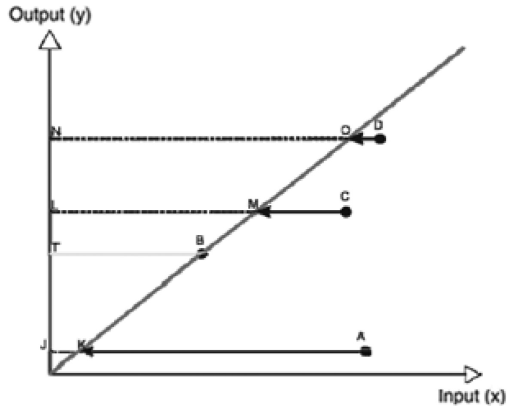

Figure 2. Graphical illustration of the input-oriented CCR model.

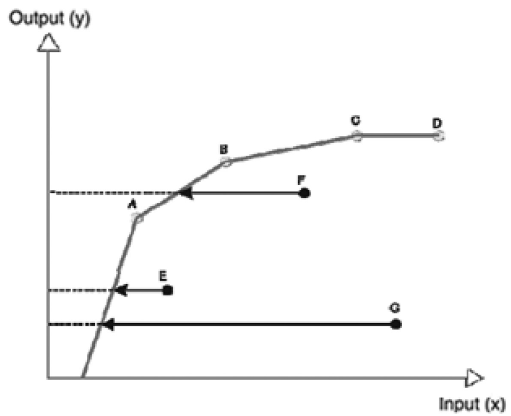

Figure 3. Graphical illustration of the input-oriented BCC model.

means the goal is to reduce the resources needed to reach that fixed value of cargo handled, evaluating the handling efficiency of the terminal.

4 PORTUGUESE PORT SECTOR

Ports can be defined as complex entities that integrate various and multiple organizations and allow the docking and shelter of ships in a secure way. The port system is part of the transport system whose function is to move passengers and freight. According Collyer (2008) the port is a national border for dynamic storage of goods, in which activities are carried out: customs, trade, health, tax, immigration, etc. It is a gate for great wealth, a supply source of offshore activities, a strategic point of the security of nations and, above all, the most important link in the logistics chain that supplies humanity.

In Portugal more than 50% of the goods imported and exported per year are carried using maritime transportation. From 2010 to 2011 an increase of 2.8% in transport by sea was verified. Next to that, break bulk cargo increased 6.5% in the same period.

4.1 *General cargo terminals*

The Portuguese port system is mainly composed by seven ports: Aveiro, Figueira da Foz, Leixões, Lisboa, Setúbal, Sines and Viana do Castelo. Even so, from these seven ports only four present a significant amount of break bulk cargo handled (Fig. 4).

In 2011, 37% of the goods handled in Aveiro were break bulk cargo. This port presents two main terminals that serve this type of cargo: Multipurpose North and Multipurpose South. The last one is under concession of the company Socarpor, but still in a public service regime. The Port of Leixões has the commercial exploitation of the activities break bulk and bulk cargo handling carried out by the TCGL (General and Bulk Cargo Terminal of Leixões).

The Port has five terminals: Dock 1 North, Dock 1 South, Dock 2 North, Dock 2 South and Dock 4 North. The major cargoes handled by these terminals include cotton, cork, timber, granite, metals, cereals, machinery, and special cargoes like transformers and wind turbines. Another analyzed port is Figueira da Foz. This port has only one general cargo and bulk terminal. The Port of Setúbal presented, in 2011, break bulk and bulk cargoes as 80% of its total cargo handled. The majority of these goods are metals, cement and timber. The terminals used for it are Tersado, Sadoport and SECIL terminal. This last one is exploited by a

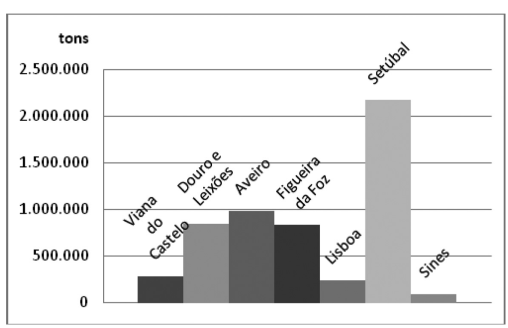

Figure 4. Amount of break bulk cargo handled in the main Portuguese ports during the year of 2011.

Table 1. Decision making units to be evaluated.

Port	Terminal	DMU
Aveiro	Terminal multipurpose north	DMU_01
	Terminal multipurpose south	DMU_02
Leixões	Dock 1 North	DMU_03
	Dock 1 South	DMU_04
	Dock 2 North	DMU_05
	Dock 2 South	DMU_06
	Dock 4 North	DMU_07
Figueira da Foz	General cargo terminal	DMU_08
Setúbal	TERSADO	DMU_09
	SADOPORT	DMU_10
	SECIL	DMU_11

Table 2. Set of variables analyzed.

Description	Type
Total quay length [m]	I1
Number of berths [Un.]	I2
Quay depth [m]	I3
Storage area [ha]	I4
Number of cranes [Un.]	I5
Cargo throughput [ton]	O1

Table 3. Collected data.

DMU	I1 (m)	I2 (un)	I3 (m)	I4 (m2)	I5 (un)	O1 (ton)
DMU_01	1150	10	12	248450	7	349453
DMU_02	400	4	7	52600	7	604117
DMU_03	455	4	10	17850	1	33642
DMU_04	520	4	10	16663	7	255516
DMU_05	670	5	11	34693	12	381887
DMU_06	690	5	11	53414	14	100260
DMU_07	400	3	12	26448	2	140350
DMU_08	462	5	5	16880	4	831475
DMU_09	864	5	10	104116	10	1100599
DMU_10	725	4	12	202397	2	473929
DMU_11	203	2	9	61000	3	588922

private company, Secil, and handles mainly bulk cargo in package form.

The DMUs chosen were these 11 terminals that handle the majority of general cargo moved in the Portuguese ports, see Table 1. As some ports have more than one terminal and some of the terminals are under private companies' concession, the DMU are going to be evaluated as independent units, and not connected to the port they belong.

5 APPLICATION

After analyzing the main Portuguese ports that handle break bulk cargo and selecting the terminals to evaluate, it was necessary to collect data about the terminals. The most reliable and complete available data about the DMUs resulted in the variables presented in Table 2, where I is an input and O an output variable.

The data collected derived from online annual reports of the ports administrations, from the seaport statistics of IPTM (Seaport and Maritime Transportation Institute) or was supplied upon request by the same entities, Table 3. All the information was related to the year 2011.

5.1 *Variables selection*

The method used for the variable selection is called Compensation Method of Single Standardization. This is a two phase method based on scenarios. The first phase is the phase where the output is set out one to one with the inputs of all DMUs to select the one input that renders the maximum efficiency compared to the general output. In the second phase the average of all efficiencies is used to calculate the efficiency index for that particular scenario. The highest efficiency index is selected and this creates the best scenario that will be used for the performance evaluation of the terminals.

This process is repeated, but now the efficiency will be calculated by two inputs and one output. One of the inputs will be the one with the highest efficiency index of the previous step, the other will be filled by the remaining. The highest efficiency index will be selected again. This continues until all variables and combinations are analyzed. Due to the limited amount of initial variables, only three best scenarios where calculated. The selection process indicated above was done with both DEA models, as shown in Table 4.

5.2 *Results*

The input-oriented DEA models were adopted to analyze the efficiency of the terminals. This means that the non-efficient DMUs are projected on the envelopment surface (efficient frontier) by reducing the discretionary inputs, and holding the outputs constant. Both the CCR and the BCC models were applied to the data with the aid of the software MaxDEA developed by Cheng Gang & Qian Zhenhua (2009). The version used is the MaxDEA 6.0 (Beta). The program has no limitation on the number of DMU to be considered and provides

Table 4. Best scenarios of each step of the models CCR and BCC.

Steps	1	2	3
DEA CCR	– Number of cranes – Cargo throughput	– Number of cranes – Number of berths – Cargo throughput	– Number of cranes – Number of berths – Storage area – Cargo throughput
DEA BCC	– Quay depth – Cargo throughput	– Quay depth – Number of berths – Cargo throughput	– Quay depth – Number of berths – Quay length – Cargo throughput

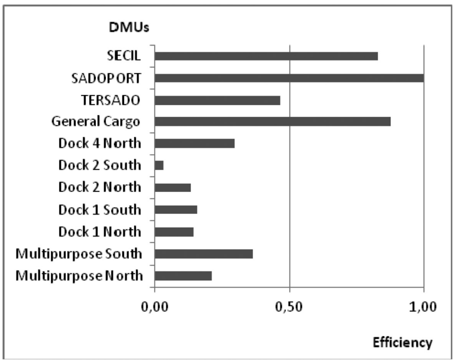

Figure 5. Terminals efficiency, scenario 1. DMUs efficiency scores when applied input-oriented CCR model with 1 input and 1 output.

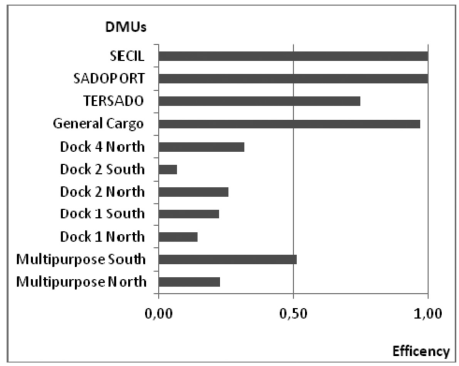

Figure 6. Terminals efficiency, scenario 2. DMUs efficiency scores when applied input-oriented CCR model with 2 inputs and 1 output.

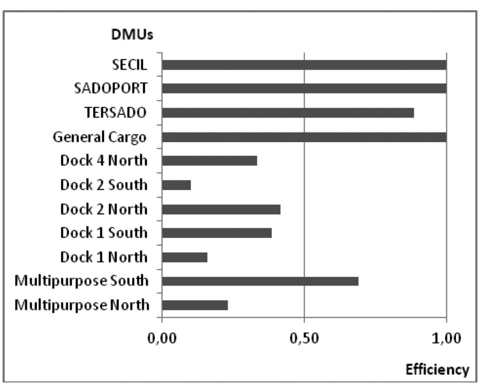

Figure 7. Terminals efficiency, scenario 3. DMUs efficiency and 1 output.

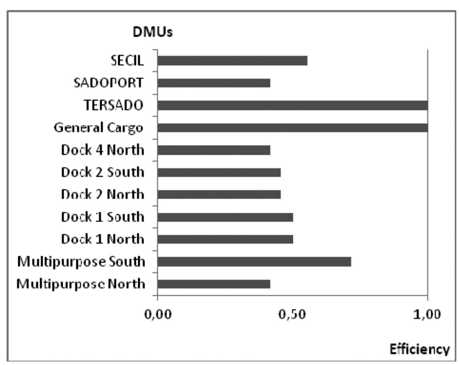

Figure 8. Terminals efficiency, scenario 1. DMUs efficiency scores when applied input-oriented BCC model with 1 input and 1 output.

an easy human interface, thus allowing great flexibility in determining efficiency.

5.2.1 *DEA CCR*

For this approach the inputs used were *the number of cranes, number of berths, storage area* and as output the *cargo throughput.*

Note that this method works with constant returns to scale, meaning that any variation on the inputs will result in a proportional variation of the output.

Figures 5–10 show the results of the analysis oriented towards the inputs with constant return, in a graphical form. Each graphic presents values

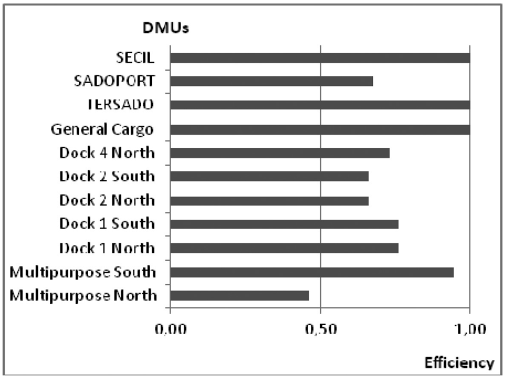

Figure 9. Terminals efficiency, scenario 2. DMUs efficiency scores when applied input-oriented BCC model with 2 inputs and 1 output.

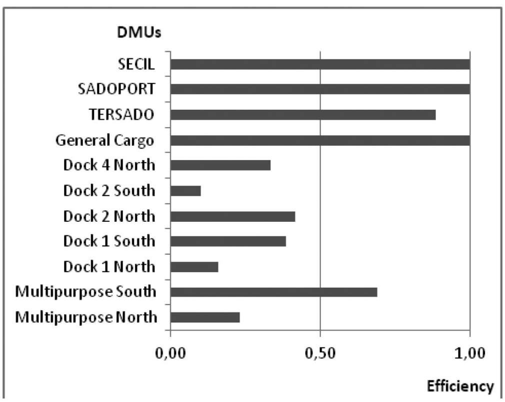

Figure 10. Terminals efficiency, scenario 3. DMUs efficiency scores when applied input-oriented BCC model with 3 inputs and 1 output.

of the efficiency index that go from 0 (inefficient) to 1 (efficient).

In all three scenarios analyzed, SADORPORT was the most efficient DMU, already from the first case, where only two variables were used: *number of cranes* and *cargo throughput*. This means that the addition of the other inputs, *berths* and *storage area* was not significantly relevant. On the other hand, Quay 2 South was the least efficient DMU in all scenarios studied. Despite of all differences in scores, all DMU presented an efficiency increase from scenario 2 to scenario 3, when the input *storage area* was added.

5.2.2 *DEA BCC*

The variables selected for this method were *quay depth, number of berths, quay length* and *cargo throughput.* With this approach the returns to scale are variable and so there is no proportionality between inputs and outputs. As the previous method, CCR, the results are presented in a graphical form with the efficiency scores going from 0 to 1.

The most efficient DMU, in all three cases studied for the BCC model, were TERSADO and General Cargo Terminal, and the most inefficient was the Multipurpose North. In these analyses scenario 2 presented the same efficiency scores as scenario 3 for all DMUs, which means that the addition of the last input, *quay length*, did not change the efficiency index of the terminals.

6 CONCLUSION

A DEA was performed on 11 terminals of the main Portuguese ports that handle break bulk cargo. The two classic DEA models, CCR and BCC, were applied and as result efficiency scores were calculated.

The CCR model indicated that from the 11 units analyzed, terminal SADOPORT, was the most efficient DMU, in all cases. The least efficient terminal the results presented was Dock 2 South. Although it presents facilities that allow the terminal to handle a large amount of cargo, when compared to the efficient DMUs as benchmark, it still does not operate sufficiently to make it efficient.

The same applies to the BCC model. Terminal multipurpose North obtained the lowest efficiency score when compared to terminals TERSADO and General Cargo, as the efficiency benchmarks.

The main points of inefficiency shown in this study were the infrastructures and the number of equipment (cranes). The increase of the quay depth of the terminal and the purchase of more productive equipment, would contribute to berth bigger ships that transport general cargo to increase the performance of the seaport.

For a higher quality performance evaluation, more data defining the seaport operation, like processes, personnel and infrastructures could be included.

This method should be applied systematically by port administrations or other maritime organizations responsible for the national planning of the ports. Its use is important just by the fact that it indicates performance indexes of the relevant factors that form the port. This enables the continuous improvement of terminals and helps introducing necessary changes to increase the efficiency levels. The competiveness of the entire logistical chain will increase and enable Portugal to become a bigger player on the international distribution market.

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A System Dynamics model for evaluating container terminal management policies

A.M.P. Santos, J.P. Mendes & C. Guedes Soares
Centre for Marine Technology and Engineering (CENTEC), Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal

ABSTRACT: A System Dynamics model is proposed to study management policies for a maritime container terminal constrained by urban and environmental pressures, which is a commonly observed case. The model allows the testing of policies related to port pricing and capacity expansion. An example application of the generic model to an existing container terminal is made. Specifically, the model is populated with data for the Alcântara Container Terminal in the Port of Lisbon. Model results show that capacity expansion seems to produce the best results in terms of increasing port throughput. Model results also show that following a policy of decreasing port price without proper capacity expansion may have a negative impact, especially in terms of revenue and profitability. Other possible detrimental consequences of such policy include crowding and a general decrease in service quality.

1 INTRODUCTION

A maritime container terminal is a distribution node of the container transport network, providing services to ships and services to freight (Rodrigue et al. 2013). The vast majority of international trade is carried out by sea (UNCTAD 2008). As an example, maritime transportation accounts for approximately 90% of the international trade of the European Union (González & Trujillo 2008). Given the interplay between trade and economic growth, a seaport can play a pivotal role in regional development (World Bank 2006). However, the same economic growth to which a seaport very often has a decisive contribution, frequently leads to a complex set of relationships between the port and its hosting city, with urban growth soon exerting strong pressure on port development as both city and port compete for the same land. In this way, many ports face urban and environmental pressures which did not exist when the terminals were first developed (Rodrigue et al. 2013; González & Trujillo 2008).

The scarcity of land available for port expansion in densely populated urban areas, and the high investment costs associated with port development, call for a careful assessment of the decision strategies of financing investments in maritime container terminals (Dekker & Verhaeghe 2012).

The amount of cargo flowing through a port is dependent on the cost incurred in by port users when deciding to use that port as part of their logistic chain. This cost, frequently termed generalized port cost, dictates the port's competitive position vis-à-vis other ports. It is composed of direct costs and indirect costs, which are essentially time-related costs. Time-related costs are intrinsically related to the service quality delivered by the port (Talley 2009; Cullinane et al. 2005). For this reason, interport competition is based on port price and service levels (Yap & Lam 2006).

The objective of this research is to compare the effectiveness of two distinct management policies, both aiming at increasing demand and profitability for a port container terminal: one policy is to decrease port price and the other policy is to expand capacity.

Maritime industry, of which port industry is a part, is widely recognized as a complex system 'composed of parts that constantly search, learn and adapt to their environment, while their mutual interactions shape obscure but recognizable patterns' (Caschili & Medda 2012). Given the systemic nature of port industry issues, it seems appropriate to use a systems approach to quantify and accurately assess the implications of investment and port pricing decisions.

It is also commonly recognized that the major players and institutions in the maritime industry should be able to understand how the impact of their policies will travel through the system influencing the behaviour of others, until the consequences of those policies travel back to them in a relationship commonly known as feedback (Ng & Lam 2011). These characteristics—particularly the ubiquitous presence of feedback relationships in the system—make port industry issues a suitable subject to be addressed with a System Dynamics (SD) approach.

This paper is organized as follows: the introduction presents the problem, its context and the research question; section 2 presents an overview of the System Dynamics approach; section 3 presents the model construction; section 4 presents a specific maritime container terminal serving as a case study for model application; section 5 presents the model results; section 6 presents the discussion; and section 7 presents the conclusions.

2 THE SYSTEM DYNAMICS APPROACH

System Dynamics (SD) was developed from control theory by Jay W. Forrester (1961). A SD model can be represented as a set of first order differential equations:

$$\frac{dx(t)}{dt} = \dot{x}(t) = f(x(t), u(t)) \tag{1}$$

where x(t) is a column vector of n state variables, u(t) is a column vector of p control variables, f(t) is the vector function characterizing the system's state and $\boldsymbol{t}$ is time.

Simulation is accomplished by translating this set of differential equations into a corresponding set of difference equations, by discretizing time into intervals of length dt (commonly referred to as 'time step'), and by stepping the system through time one dt each step (Sterman 2000).

Other tools commonly used within the SD approach include: graphs of Behaviour Over Time (BOT); Causal Loop Diagrams (CLD) and systems archetypes.

BOTs are graphs depicting the history of a variable over time, which are particularly useful for revealing 'signature' patterns that may suggest that a particular structure is present (thus representing some particular systemic process).

A CLD is a graphical representation of one or more closed loops depicting cause-and-effect linkages between variables. CLDs constitute a means of representing a system's feedback structure, with reinforcing loops indicated by an *R* enclosed within a curved arrow, and balancing loops similarly indicated by a *B* (Sterman 2000).

Systems archetypes are generic structures that capture behaviours commonly observed in dynamic systems. Typically, a combination of one or more archetypes may explain the dynamics of a particular problem. Archetypes serve as a starting point from which a clearer articulation of a business story or issue can be achieved (Anderson & Johnson 1997).

The use of CLDs, BOTs and systems archetypes allows the articulation of a dynamic problem as well as a tentative account of its possible causes and structural depiction. However, CLDs do not take dynamics into account, and for this, simulation is necessary.

This research puts a special emphasis on identifying the structure of a container terminal competitiveness through the use of appropriate archetypes. The approach followed can be presented as:

1. Defining the problem in terms of dynamic behaviours, representing relevant variables as BOTs;
2. Identifying the structure responsible for those behaviours (generally with the use of archetypes);
3. Identifying stocks or accumulations in the system's structure and their respective inflows and outflows;
4. Developing a behavioural model capable of reproducing the dynamic problem of concern (computer simulation);
5. Gaining insights into the system's functioning and drawing conclusions on the outcome of applicable policies.

The model is built and simulated in VENSIM® (by Ventana Systems inc.), a SD modelling software. For details on the SD approach see Sterman (2000).

3 MODEL CONSTRUCTION

Any seaport located in an urban area will eventually meet a limit for its expansion. For this reason, the dynamic evolution of throughput in ports typically exhibit the logistic or S-shaped growth trend (Ng & Lam 2011). Figure 1 shows the throughput

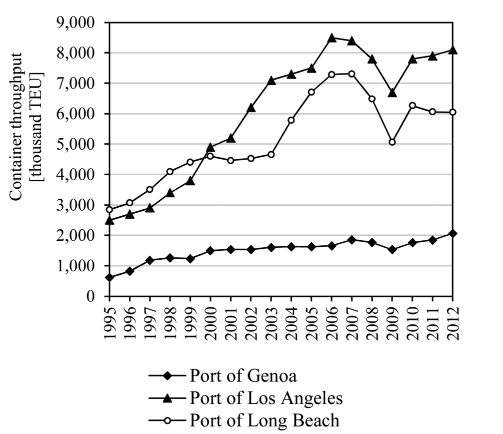

Figure 1. Throughput behaviour over time graphs for ports facing urban constraints to port development (Source: based on the respective Port Authorities data).

BOT graph for three seaports known to face urban pressure constraints (Port of Los Angeles, Port of Long Beach and Port of Genoa).

There are dynamic behavioural patterns common to the three ports under consideration. Some more or less pronounced growth in throughput was initially observed followed, after some time, by stagnation.

Ng & Lam (2011) provide a more detailed analysis for the ports of Los Angeles and Long Beach, and Rosa & Roscelli (2009) and Caballini & Gattorna (2009) for the Port of Genoa. Care should be taken when analysing the noticeable drop in throughput for the years 2008 and 2009 as these correspond to the years when the current economic crisis started to have full effect (Notteboom 2013).

The historical behaviour of throughput for ports under urban pressure seems to mimic the behaviour depicted by the 'limits to growth' archetype, where actions that are initially successful in causing growth cause more of the same actions to be undertaken. However, at some point in time, the system eventually meets a limit which causes growth to slow down, or even come to a halt (Senge 1990).

Larsen et al. (1997) described the 'limits to growth' behaviour for a service company facing the problem of delivering a service at a desired quality level on the basis of expectations from shareholders and corporate owners. Ng & Lam (2011) use it to describe the dynamics of limits to port growth. Figure 2 represents the archetype for a container terminal in the form of a CLD.

Figure 2 indicates that an increase in *handled containers* leads to an increase in *net income* (as shown by the '+' sign in the arrow connecting the two variables). In turn, an increase in net income will lead to an increase in *capacity investments*, and, thereby, in *installed capacity*. An increase in installed capacity will lead to a decrease in time spent in port per ship (as shown by the '–' sign) as more resources become available for each ship. A decrease in time spent in port, in turn, will lead to an increase in *container terminal attractiveness*.

Usually, the effect is not immediate, and it may take some time for port users to adapt their

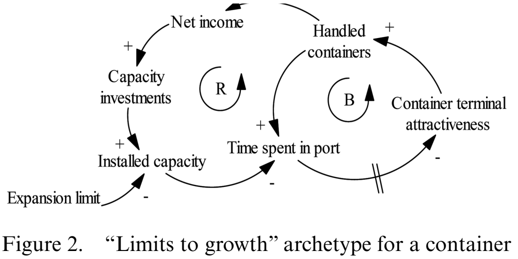

Figure 2. "Limits to growth" archetype for a container terminal (adapted from Ng & Lam 2011).

behaviour to the new perceived service quality. So, there is a delay between the offering of a different service quality and the corresponding change in port demand. A delay is represented in a CLD in the form of two vertical lines crossing a causal arrow. Finally, an increase in the container terminal's attractiveness will lead to an increase in handled containers, in this way closing the reinforcing loop (*R*).

An increase in handled containers will not only lead to an increase in net income but also to an increase in time spent in port. This occurs because ships (and their cargo) compete with each other for the limited pool of the terminal's resources (quay length, quay cranes, trailers, etc). As capacity utilization increases, the time a ship must wait until its service is complete will also increase. An increase in time spent in port will cause the container terminal's attractiveness to decrease. In turn, this will lead to a decrease in handled containers, in this way closing the balancing loop (*B*).

The structure described by the CLD in Figure 2 suggests that if the aim is to increase the amount of handled containers, then, capacity investments must be made, as this is the only way by which the reinforcing loop operates. If capacity investments are not made, this cuts off the reinforcing loop, and the balancing loop will be the only one at work.

Additionally, the majority of maritime ports around the globe eventually meet a limit to their capacity expansion, as a result of insertion in densely populated urban areas (Trujillo & Nombela 1999). A limit to port capacity expansion is represented in Figure 2 as an external input (i.e., it does not depend on other model variables).

According to the proposed methodology, the step after identifying the structure responsible for the observed behaviour is to translate this structure into a stock and flow diagram, in order to make it possible to run a simulation.

The translation of the container terminal's CLD into a stock and flow formulation is presented in Figure 3. In stock and flow diagrams, stocks (or levels) correspond to integrals and are represented as box-like shapes while flows (or rates) correspond to derivatives and are represented as double arrows pointing into or out of the respective stocks. Single line arrows depict dependence between variables.

3.1 *Scope*

The generic container terminal featured in the model is assumed to be managed by a private contractor, whose main goal is profitability. As such, investment decisions are dependent on terminal performance, which is dictated by the system's dynamic behaviour. Therefore, the investment decision is considered to be an endogenous vari-

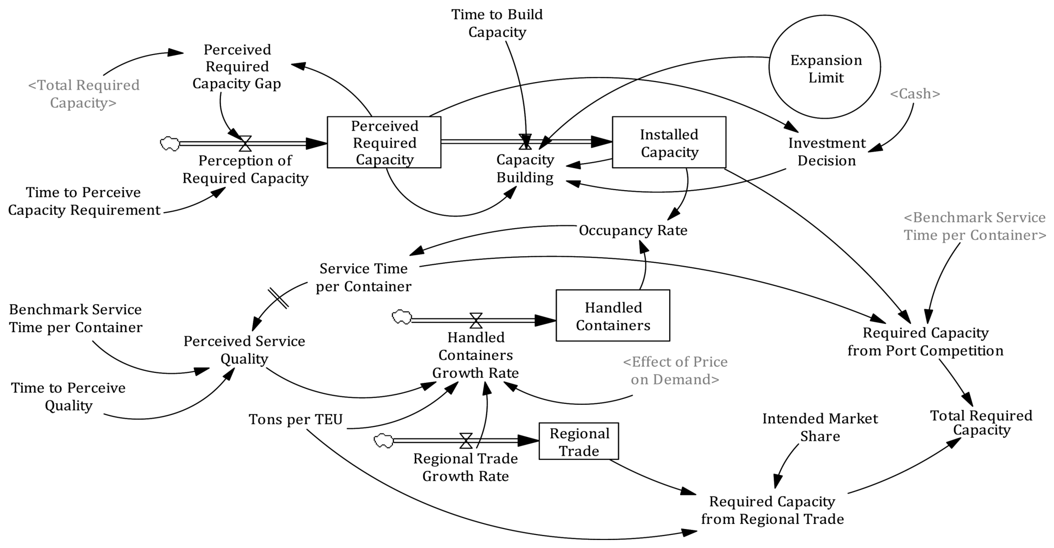

Figure 3. Stock and flow diagram for a container terminal constrained by urban pressure.

able, dependent on the perception of the need to invest and cash availability.

Capacity is expanded as a result of the terminal operator's investment decision and fund availability. The number of handled containers is the result of the port users' response to the quality of the service delivered by the terminal and its pricing policies. Investment in capacity is dependent on the perception of the need to make such an investment and also on cash availability, both of which are outcomes of the system's structure.

Additionally, cost recovery price is an endogenous variable as the costs in which the terminal incurs in are determined by the model's structure. The model assumes a mechanism of average cost pricing, in which price is set at the average production cost (including fixed and variable costs) plus a margin for profit (or markup, usually expressed as a percentage increase above the cost-recovery price level).

Authors using a SD approach to address port industry issues have taken several approaches concerning the relation between economic factors and port throughput. Carlucci & Cira (2009) consider port throughput and economic development in the hinterland to be related through a mutually reinforcing loop (i.e., the higher the economic development in the hinterland, the higher the port throughput and vice-versa). Castillo et al. (2006) take the economic growth in the region served by the port as an external input, independent of port throughput.

This research follows an approach similar to that of Castillo et al. (2006). Regional trade—a proxy for regional economic development—is used as an external input. This research does not aim at assessing the impact of a container terminal on the regional economy, so the regional economy will be assumed independent of the container terminal throughput.

Table 1. Model boundary.

Endogenous variables	Exogenous variables
• Installed capacity	• Regional trade
• Handled containers	• Markup
• Capacity investments	• Benchmark time in port per container
• Cost-recovery price	• Limits to capacity expansion

The choice of markup is a contractor decision and, by assumption, limits to port capacity expansion can be imposed on the contractor. Both are model inputs or exogenous variables. The average time in port per container in competing ports is also an exogenous variable that will be used as benchmark.

Table 1 presents the boundary for the SD model.

The time horizon for the model simulation spans from 1995 to 2030. The main reason for this choice was whether this time horizon was sufficient for the dynamical behaviour of the variables under study to unfold and, in particular, to exhibit behaviour typically associated with certain system archetypes.

In order to assess the financial performance associated with each alternative policy, the model is composed of two sub-models: one concerning the physical operations that take place in the terminal, which will henceforth be referred to as 'terminal operations sub-model'; and another concerning the financial implications of each management policy based on commonly used financial ratios, which will henceforth be referred to as the 'financial sub-model'.

The terminal operations sub-model allows the assessment of the effect of alternative policies on port demand. In turn, the financial sub-model allows the calculation of most of the financial ratios commonly used to measure profitability, liquidity, asset management, leverage, risk, etc.

Operational performance is assessed in terms of handled containers, and financial performance is assessed through the analysis of net income per container. The sub-models are interrelated, each one producing inputs to the other, as shown in Figure 4.

3.2 *Terminal operations sub-model*

The assumption to model capacity expansion investments that before an investment is made, it must be perceived as necessary. The level variable called *perceived required capacity* is meant to accumulate that perception.

There are essentially two reasons for ports to invest in extra capacity: competition among ports and demand growth due to external factors, such as economic development in the hinterland (Dekker & Verhaeghe 2012). Required capacity is modelled as a function of two variables: regional trade volume, and difference between the actual *service time per container* and the *benchmark service time per container*. This difference models the drive for port investments through the mechanism of interport competition based on *perceived service quality*. That is, lengthy service times (arising from high occupancy rates) indicate that extra capacity should be added to maintain the same service quality, and too fast service times may indicate excess capacity, hindering further investments.

If required capacity has a positive value and there is enough cash to make the investment, then the flow called *capacity building* accounts for the transformation of *perceived required capacity* into *installed capacity*.

3.3 *Modelling the perception of service quality*

Time-related costs are essentially determined by port capacity (World Bank 2006). In particular, the length of a ship's service time is an important determinant of port users' choice (Panayides & Song 2012). The major determinant of port service quality is capacity investments, and the main economic benefit of capacity investments is the ability to reduce ship turnaround time (World Bank 2006).

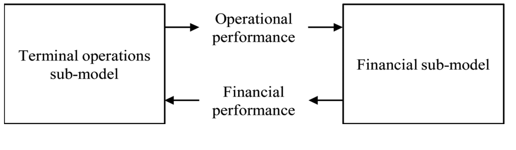

Figure 4. Interrelation between the two sub-models.

The time a container spends in the port system can be approximated with the use of Little's formula for the M/M/1 queue (Gross et al. 2008):

$$W = E[T] = s/(1-\rho) \qquad (2)$$

where W is the expected time a container will spend in the system, s is the average service time per container, and ρ is the utilization factor (i.e., occupancy rate).

This formula shows that, for capacity usage levels above the 70–80% threshold, there is a steep increase in time spent in the system. This is in agreement with the widely used rule of thumb according to which an occupancy rate above 70–80% leads to a significant drop in service quality as queuing and service times increase to intolerable values (Drewry Research 2010).

To assess service quality, users continually compare time spent in port with some benchmark. According to Drewry Research (2010), the optimum level of occupancy for a container terminal is around 65%. The service time corresponding to this occupancy rate is considered the benchmark in this research. The following formulation maps the perceived service quality in the interval $\Re \rightarrow [-1,1]$:

$$y = x/(|x|+1) \text{ [units: dimensionless]} \qquad (3)$$

where y is the *perceived service quality* and x is the difference (*benchmark service time per container—service time per container*). According to this formulation, when the terminal achieves a time in port per container that is lower than the *benchmark*, the *perceived service quality* will have a positive value.

3.4 *Financial sub-model*

To assess the financial implications of management policies, the financial sub-model is largely based on the work of Yamaguchi (2003), who proposes a SD approach for modelling corporate financial statements: the balance sheet items are stocks (i.e., they represent accumulation of quantities), and the income statement items are the corresponding flows (i.e., they represent the rate of change of balance sheet items).

Typically, current assets are considered to be composed of accounts receivable, cash and inventory items. However, inventory items were not accounted for in the model presented here.

The reason for this lies in the fact that a container terminal is a service based company. For service based companies, inventory items usually represent a relatively small share of its assets. For example, for the Alcântara Container Terminal, the container terminal which will be used as a case study for model application, inventory represents approximately 0.1% of current assets while accounts receivable and cash represent approximately 80% and 20% of current assets (Liscont 2009:11).

Figure 5 shows the stock and flow diagram for the container terminal operator's total assets, while the stock and flow diagrams for the company's liabilities and shareholer's equity are shown in Figures 6 and 7, respectively.

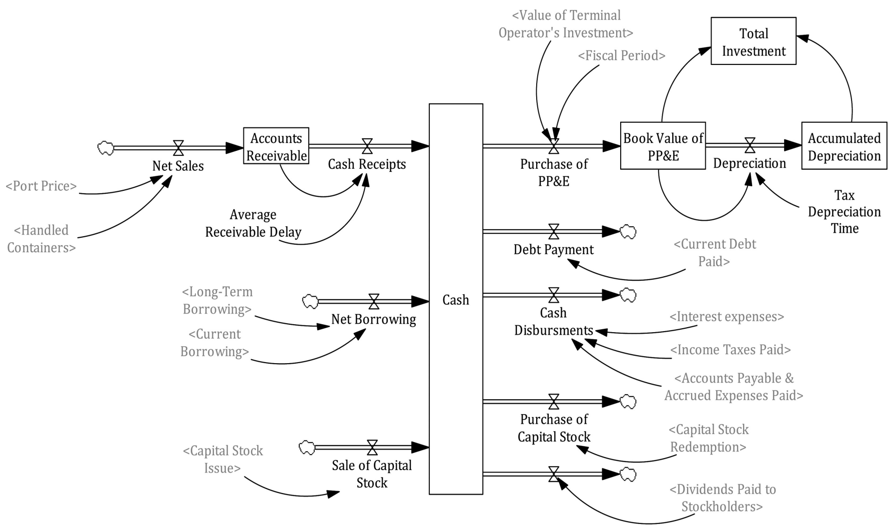

Figure 5. Stock and flow diagram for the firm's assets considered in the model.

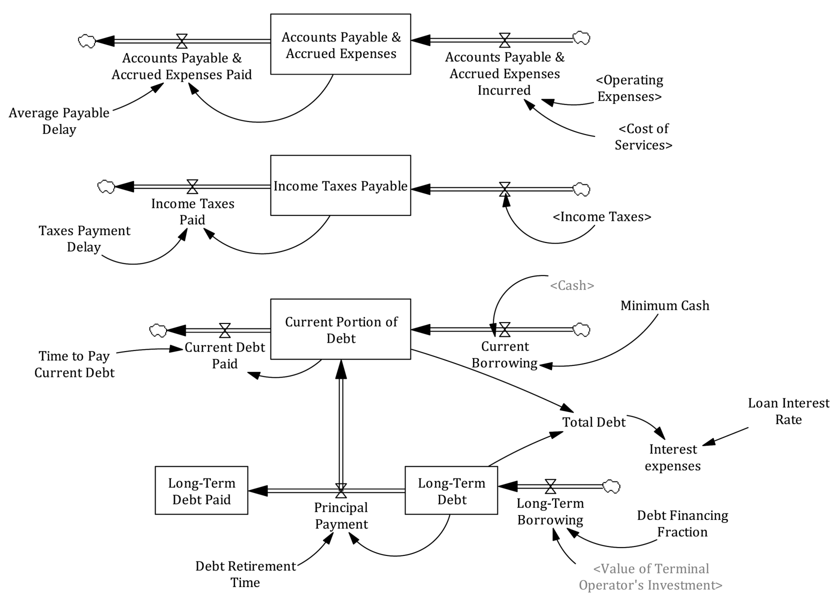

Figure 6. Stock and flow diagram for the firm's liabilities considered in the model.

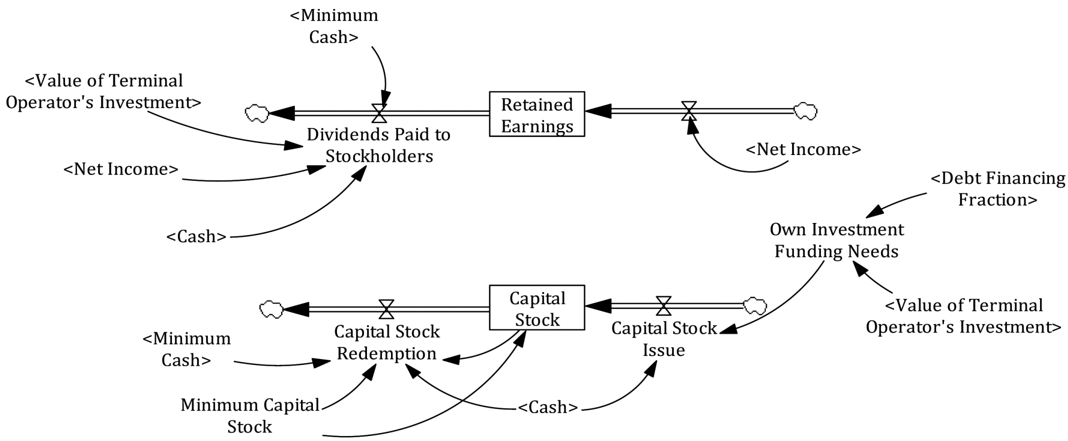

Figure 7. Stock and flow diagram for the firm's shareholders equity.

4 MODEL APPLICATION TO A CASE STUDY

The Alcântara container terminal, in Port of Lisbon, was chosen as a case study because it faces constraints on capacity constraints resulting from urban and environmental pressure, which has been undermining the possibility for further growth in demand (Consulmar 2007). In particular, labour related constraints and lack of good land accessibility are among the main causes for the observed stagnation. Despite the possibility of the SD methodology to account for specific issues regarding capacity constraints, in this paper, capacity and its respective restrictions are dealt with in a general sense (i.e., no distinction is made between yard, berth, accessibility or labour related capacity constraints).

The Alcântara Container Terminal is especially prepared for deep sea traffic and is currently concessioned to Liscont—Operadores de Contentores, SA. It has a total area of approximately 120,000 square meters, a static yard capacity of 8,500 TEU, and a theoretical capacity for handling 350,000 TEU per year. The quay length is 630 meters and the berth depth is approximately 13 meters.

Figure 8 shows the container throughput for the Alcântara container terminal from 1995 to 2012. There was a noticeable increase in throughput in the years between 1995 and 2003.

Then, throughput stopped increasing and began to oscillate around a mean value of about 225 thousand TEU, a behaviour which is typical of the limits to growth archetype.

After completing the structure, the model physical parameters were populated with data from the terminal. Financial data were retrieved

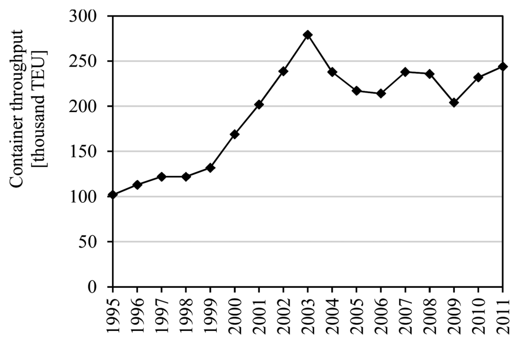

Figure 8. Container throughput at Alcântara Container Terminal between 1995 and 2012 [source: APL (2013)].

from Liscont's financial annual reports (Liscont 2009–2011), the Court of Auditors audit to the public-private partnership for the Alcântara container terminal (Tribunal de Contas 2009), and the legal framework documents for the Alcântara container terminal concession (Diário da República 1984).

The comparison between simulation runs and historical data allowed for model validation and testing management policies.

4.1 *Results*

A commonly used test for building confidence in SD models is the reproduction of historical behaviour, which is part of the behaviour reproduction test. Figure 9 depicts model results and historical data for throughput at Alcântara container terminal.

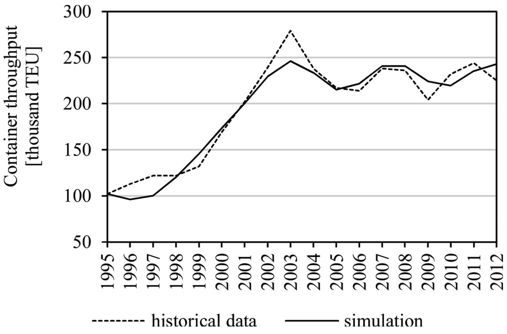

Figure 9. Base model run results and historical data for Alcântara container terminal throughput.

Table 2. Error analysis.

Variable	Container throughput [thousand TEU]	
RMSPE [%]	7.4%	
MSE	172.0E06	
Inequality statistics	U^M	0.011
	U^S	0.012
	U^C	0.976

Both curves show the same pattern of behaviour, with a steady growth in the initial stages and an ensuing stagnation and oscillation around an average value of approximately 225 thousand TEU.

Sterman (1984) set up a series of statistic tests judged appropriate for SD models. These include the Mean-Square-Error (MSE):

$$MSE = (1/n)\sum_{t=1}^{n}(S_t - H_t)^2 \tag{4}$$

where n is the number of observations; S_t is the simulated value at time t; and H_t is the historical value at time t. Another commonly used error measure is the Root-Mean-Square Percent Error (RMSPE):

$$RMSPE = \sqrt{(1/n)\sum_{t=1}^{n}[(S_t - H_t)/H_t]^2} \tag{5}$$

The inequality statistics allows the decomposition of the mean-square-error:

$$U^M = (\bar{S} - \bar{H})^2 / [(1/n)\sum_{t=1}^{n}(S_t - H_t)^2 \tag{6}$$

$$U^S = (\sigma_S - \sigma_H)^2 / [(1/n)\sum_{t=1}^{n}(S_t - H_t)^2 \tag{7}$$

$$U^C = [2(1-r)\sigma_S \sigma_H] / [(1/n)\sum_{t=1}^{n}(S_t - H_t)^2 \tag{8}$$

where $\bar{s}$ and $\bar{H}$ are the means of S and H; σ_S and σ_H are the standard deviations of S and H; r is the correlation coefficient between simulated and historical data; U^M, U^S and U^C reflect the fraction of the mean-square-error due to bias, unequal variance, and unequal covariance, respectively.

Table 2 shows that the covariation component of MSE (U^C) is much higher than the bias (U^M) and the variance (U^S) components. According to Sterman (1984), it is likely that a large random component in one of the variables is responsible for a large U^C. Noise or cyclical modes may be present in the historical data and were not captured in the model. Sterman (1984) adds: 'A large U^C indicates the majority of the error is unsystematic with respect to the purpose of the model, and the model should not be faulted for failing to match the random component of the data.'

In particular, a cyclical mode, accounting for a large U^C, can be explained in the light of the 'limits to growth' archetype with oscillating behaviour, the oscillation resulting from the delay between the offering of a given service quality and the perception of that same service level on the part of port users, as detailed in the beginning section 3.

5 MANAGEMENT POLICY ANALYSES

This section contains a brief overview of management policies that could lead to an increase in cargo throughput at Alcântara container terminal. The policies tested with simulation were:

1. Change in port price;
2. Expansion of capacity (500,000 TEU/year);

These policies are introduced in 2012, and followed from that moment onwards. From 1995 to 2012—the last year for which there is historical data to compare the model results to—all scenarios follow the same policy (the 'business as usual' baseline).

Figures 10, 11 and 12 show the impact of the tested policies on port throughput, perceived service quality and net income per TEU.

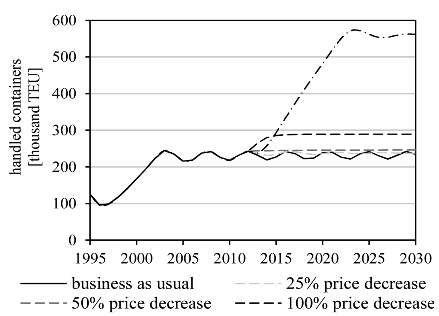

Figure 10. Impact of the tested policies on port throughput.

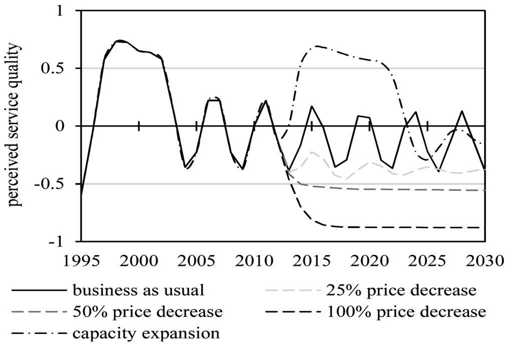

Figure 11. Impact of the tested policies on perceived service quality.

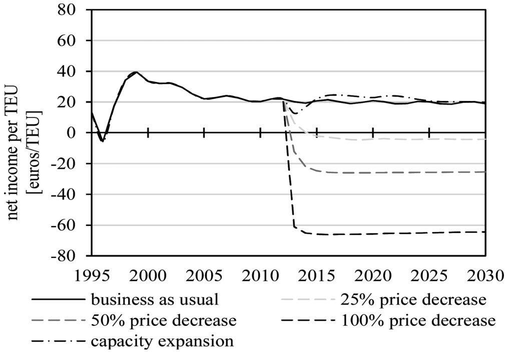

Figure 12. Impact of the tested policies on net income per TEU.

6 DISCUSSION

Model results show that decreasing port price seems to be a relatively ineffective policy both in terms of increasing port throughput and profitability. The increase in port demand when port price is decreased is somewhat insignificant, confirming that port demand is highly inelastic to price, particularly for high congestion levels (Bae et al. 2013).

However, decreasing port price does have an initial positive impact on port demand that is greater than that observed when a policy of capacity expansion is followed. But, as no capacity expansion is made to accommodate the initial increase in port demand, crowding soon occurs as port users compete for the limited pool of port resources. This leads to a degradation of service quality as shown in Figure 11. Moreover, Figure 12 shows that decreasing port price has a negative impact on net income per container, as the small increase in port demand is not enough to compensate for the decrease in port price and the resulting revenue (i.e., the product of handled containers and port price) is lower than that of the business as usual baseline.

Furthermore, model results suggest that capacity expansion produces the best results in terms of increasing both throughput and service quality.

7 CONCLUSIONS

A System Dynamics model allows the study of management policies that could lead to an increase in throughput and profitability for a container terminal. To this end, two types of management policies are tested—expanding port capacity and changing port price—with model results suggesting that capacity expansion is the most effective management policy for increasing port demand.

Trying to increase port demand and profitability by following a policy of a lower port price, however, seems to produce the reverse of the desired outcome. When a decrease in port price is not accompanied by proper capacity expansion, crowding soon leads to degradation in service quality.

As service quality is a major determinant of port users' choice, this has a negative impact on port demand, which does not increase as much as it could expected from a lower price. As a consequence, all positive benefits that could arise (and which are actually felt in the initial stages of the implementation of such policy) are soon lost. Moreover, as the slight increase in port demand is not enough to compensate for the decrease in port price, a strong negative impact in net income is also observed under a policy of lower port price.

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Methodology and tools to design container terminals

T.A. Santos, M. Marques & C. Guedes Soares
Centre for Marine Technology and Engineering (CENTEC), Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal

ABSTRACT: This paper presents a methodology for determining the characteristics of container terminals, allowing a better understanding of the suitability of existing methods for their basic design. This methodology starts from a traffic forecast and uses different approaches, including a statistical database and computational methods, to derive the terminal characteristics. The results of the different approaches are then compared aiming at their demonstration. This methodology is applied to a case study which is a deep water terminal in Lisbon that has been suggested recently. The possible economic reasons for such a terminal, including a forecast of container traffic demand in a 20 year horizon, are presented. Based on these, a basic design of the required facilities is presented, including yard areas, quay lengths and quay and yard equipment. This case study, while being an example of application of the methods proposed, can however produce results that, despite the academic nature of the study, can help the public discussion of this project.

1 INTRODUCTION

Maritime transportation is an essential element of the economic activity of all countries as it is responsible for a large amount of import and export activities of goods and of main energy and food supplies. Ports are a key element in this chain and it is very important that they are well optimized and efficient in their operation not to delay the transportation process.

Presently the various countries have their main ports in operation and thus the studies that are made nowadays often concern the improved operation of the existing terminals (eg. Silva et al. 2014). In rare situations the creation of a new port may still be posed and thus the availability of methodologies for its design are important.

The design and optimization of container terminals requires simulation and planning tools suited to the assessment at different levels of detail. This paper aims at developing a methodology for terminal planning and basic design tools for that purpose.

The paper starts with the presentation of a methodology for terminal preplanning starting with traffic forecasts and progressing towards infrastructure and superstructure planning. Different calculation methods are implemented in calculation tools and used to derive the area, quay length, lay-out, equipment necessary for the forecasted traffic. Finally, the main parameters of the proposed solution are compared with a database of parameters of container terminals, to assess if the calculated parameters are in line with industry benchmarks. The results of these methods are first validated against the first phase of the container terminal in Sines (Terminal XXI).

The Portuguese government has recently unveiled a study on the priority transport infrastructures for the country (GTIEVA 2013). This study identifies the ports, railway lines and airports which are seen as priorities for the country. Among the priority projects, many are port related projects, including a number of container terminals, as well as improvements in sea approaches to ports and interconnections with road and rail networks. Examples of proposed projects are the expansion of a container terminal in Leixões, the expansion of Terminal XXI in Sines, a new deep water terminal in Lisbon and the improvement of efficiency of existing terminals in Lisbon.

As a case study, a possible technical solution is developed for the new deep-sea container terminal in Lisbon that was one of the priority projects identified in the GTIEVA study, which should revitalize the port of Lisbon.

Conclusions regarding the different methods developed and the characteristics of such Lisbon deep water terminal are drawn.

2 METHODOLOGY FOR CONTAINER TERMINAL PLANNING

The planning of a new container terminal starts with the identification of the volume and nature of the container traffic requiring such terminal, also considering if it is a regional, gateway or transhipment terminal. The selection of suitable locations involves the consideration of several factors, such as, for example, those given in Thoresen (2003). A list of such factors should comprise at least the following: availability of sufficient area, possibility of future extension, availability of sufficient water depth, availability of hinterland connections, accessibility and distance from sea, nature of subsoil and risk of geotechnical problems, shelter from waves and wind, shelter from current, earthquake danger, environmental impact and social and economic impact.

Once a suitable location has been selected and the necessary environmental and economic studies have been completed, the planning of the container terminal can start. This activity can be divided in different levels, according with Bose (2011), namely in operational, superstructure and infrastructure levels. The operational level deals with problems ranging from the day-to-day operations to tactical and strategic options for existing terminals. In this level, simulation studies play an important role in developing solutions for identified problems and studying detail solutions for expanding operational capacity or optimizing existing assets (Silva et al., 2014).

In the infrastructure level, planning of required areas and quay lengths and terminal connections to external networks are the main tasks. In the superstructure level, the main objective is to plan the layout, quay and yard equipment, buildings, illumination, fencing, manning and supply and disposal network. In both levels, most notably in infrastructure building, a number of tasks fall in the area of civil engineering, which is covered in specialized literature such as Thoresen (2003) and UNCTAD (1985).

In superstructure planning it is usual to distinguish between the main areas in a terminal: quay, yard and landside. For these areas, the depth of the analysis varies whether it is a preplanning or detailed planning study. This study has as scope the development and application in a case study of a methodology for preplanning the infrastructure and superstructure of new container terminals, including also a traffic forecast, as shown in Figure 1. Mohseni (2011) presents a similar methodology but without considering the traffic forecast.

The first phase in the planning of a container terminal is the traffic forecast which will allow determining the pattern of arrivals (number, type, day and time of ships). Other important outputs are the number of TEUs handled per ship, the overall TEU throughput, dwell times, hinterland modal split and arrival pattern for hinterland traffic. These variables will form the so-called project requirements.

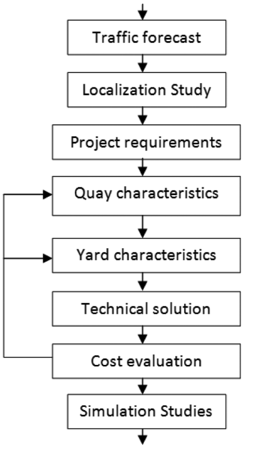

Figure 1. Methodology for container terminal planning.

A second phase is the planning of the quay length, layout, depth of water and quay height above water, on the infrastructure side of the problem. On the side of the superstructure, the number and size of quay cargo handling equipment (generally gantry cranes) are planned. These characteristics are largely determined by the results of the traffic forecast regarding the pattern of ship arrivals.

A third phase is the planning of the yard size, shape, layout (disposition and number of container stacks or blocks), largely determined by quay length and layout, site natural characteristics and available land area. Also in this phase, the yard handling equipment is determined as required by the quay wall throughout under normal and peak conditions.

In the preplanning level several options are frequently identified as regards layout and type of equipment, with decisions being made at subsequent detail planning studies. Cost plays a determining role in selecting the type of handling equipment, the degree of automation to be considered and the way terminal area is made available. Nowadays, simulation studies will be carried out to test the operational performance of the terminal and identify specific areas, operations or equipment requiring optimization. An example of such studies is given in Saanen (2004).

3 CONTAINER TERMINALS IN SOUTHERN PORTUGAL

3.1 *Rationale of new container terminal in Lisbon*

The Portuguese government has announced early in 2013 a plan to revitalize the port of Lisbon.

This plan includes the development of a new deep water container terminal. The terminal would have a capacity for 2,000,000 TEU per year and one possible location is at the mouth of the river Tagus, in the south bank, as shown in Figure 2. One proposed layout is shown in Figure 3, taken from Cerejeira (2013).

This project has become immediately the focus of interest and criticism coming from public opinion, municipalities, port operators in competing ports, environmentalists and associations of dwellers.

The main advantage of this project is the possibility to increase the container handling in the port of Lisbon, which in recent years has tended to stagnate. A discussion of the problems involved can be found in Santos et al. (2014). Furthermore, the depth of the water allows the handling of larger containerships then currently possible, including the largest ships with a draft of over 16 m. This would require maintaining a water depth of 18 m in the navigation canal.

Among the disadvantages of the project is the fact that 70% of the containers currently handled in the port of Lisbon are coming from or going to locations in the north bank of the river and the cost of developing the necessary road and railway connections. Also, there are concerns over the environmental impact of the works.

Figure 2. The area of Trafaria at the mouth of river Tagus.

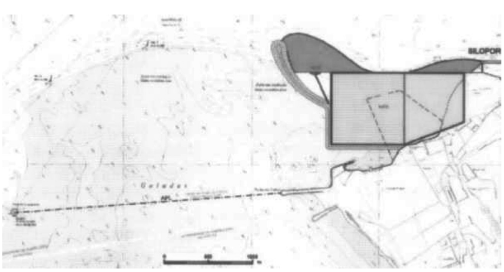

Figure 3. Proposed Trafaria container terminal—downstream of Silopor, Cerejeira (2006, 2013).

In any case, it is necessary to carry out several studies, including traffic forecast studies, environmental impact study, coastal dynamics study, terminal dimensioning and lay-out study and, finally, simulation studies for fine tuning of details of the terminal lay-out. In parallel, a cost-benefit analysis needs to be carried out.

This paper is based on the assumption that this new deep water terminal could consist of a new transhipment terminal along with a terminal dedicated to the existing regular liner services in the port of Lisbon, thus using these services to distribute the containers carried from Asia via the Suez Canal, throughout the entire Atlantic basin. This would certainly have large benefits for the competitiveness of the Portuguese economy and exports.

Taking in consideration the way shipping and port industry is organized, in this market segment, it is very important to ensure that a global terminal operator becomes involved in the project, so that foreign investment supports most of the cost of this large project. Such partner is also essential because of its contacts with liner companies and technical expertise necessary to make the project a success.

3.2 *Operational paradigm in Lisbon and Sines*

The port of Lisbon possesses two main container terminals with long established regular liner services, from such shipping lines as Maersk. However, it does not possess regular services connecting directly to Asia, since most ships generally employed in these trades cannot berth in these terminals due to low depth. The terminals in Lisbon are Liscont and Sotagus, shown in Figure 4. Liscont can

Figure 4. Liscont, Sotagus and Sines container terminals.

Table 1. Characteristics of container terminals.

Characteristic	Liscont	Sotagus	Terminal XXI	Sadoport	TML
Handling capacity (TEU)	350000	450000	1000000	~650000	~85000
Quay length (m)	630	750	730	725	480
Quay water depth (m)	14	10	17.5	12	6
Area (ha)	12	16.5	24	20	4.8
Yard capacity (TEU)	8592	10300			2300
Ground slots (TEU)	~1835	~2374	~4200		
Maximum size of ships (TEU)	5000	2000	18000	5000	~700
Quay gantry sub-Panamax	–	1 (22 m)	–	–	–
Quay gantry Panamax	2 (14 rows)	3 (35 m)		1	–
Quay gantry post-Panamax	1 (19 rows)	1 (40 m)	3 (20 rows)	1	–
Quay gantry super post-Panamax	–	–	3 (23 rows)	–	–
Number of tractors	15	22			
Number of RTGs	7	6	15	None	–
Number of RMGs		2		None	–
Stacks	10	12	25		3
Ground dimensions stacks (FEU)	12.5 × 7 17 × 7 10 × 7	17 × 12 17 × 5 10.5 × 5	14 × 6		~10 × 6 ~9 × 6 –

handle yearly 350,000 TEU and Sotagus 450,000 TEU. The terminal in Sines has now capacity for 1,000,000 TEU and the most important deep sea services which call in Sines are from MSC.

Table 1 shows a comparison of the main characteristics of Liscont, Sotagus and Terminal XXI. It is worth noting that the latter terminal is capable of receiving much larger ships and is accordingly better equipped and fitted with a larger yard. This table also includes two other terminals in southern Portugal, Sadoport (Setúbal) and TML (Lisbon), but these handle smaller amounts of containerized traffic mainly for the Portuguese islands (Azores and Madeira) and short sea trades.

Figure 5 shows the liner services network of the ports of Sines and Lisbon. It is important to take into account that this is a highly dynamic reality with constant adaptations introduced by shipping companies in response to ever evolving market conditions. In Sines, the first line was the Lion Service, connecting Sines to East Asia, but a network of services in the Atlantic Ocean has since then been developed.

Figure 6 shows the liner network in Lisbon. The service to East Asia came after the network in the Atlantic had been developed and only operated for a short time. Figures 5 and 6 also show the approximate size of the ships scheduled for each major service, being possible to conclude that the average size of the ships serving Lisbon is much smaller than the ships serving Sines in the same lines. It is worth point out that there are already services providing useful feedering between ports in the western Atlantic coast of the Iberian Peninsula, calling both at Lisbon and Sines.

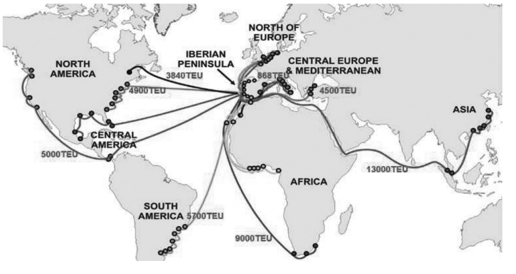

Figure 5. Liner services in the port of Sines (APS, 2013).

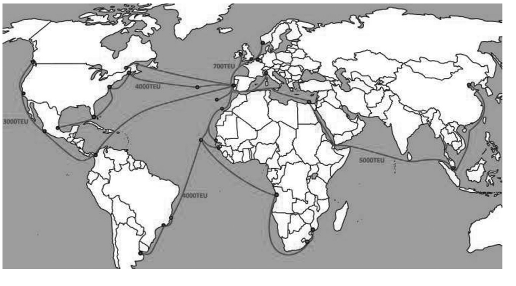

Figure 6. Liner services in the port of Lisbon (own elaboration from APL 2014).

A detailed examination of the services that call in Lisbon and Sines has been carried out based on the information provided in the websites of port administrations, aiming at characterizing current liner transport supply. Table 2 shows the number of ships currently arriving each week at these ports.

Table 2. Estimate of number of ships calling each terminal.

Sotagus	Liscont	Terminal XXI
2 ships of ~450 TEU	2 ships of ~200 TEU	5 ships of ~900 TEU
8.5 ships of ~700 TEU	7 ships of ~700 TEU	2 ships of ~1500 TEU
1.5 ships of ~2000 TEU	7 ships of ~2000 TEU	3 ships of ~4500 TEU
	1.5 ships of ~4000 TEU	3 ships of ~5500 TEU
		1 ship of ~9000 TEU
		1 ship of ~13000 TEU
12 ships	17.5 ships	15 ships

For Sotagus and Liscont terminals there is information on the type of each service (weekly or less), but for Sines no such information could be found. However, in this case, the container terminal is known to have currently 15 liner services, therefore at most 15 ships will call in weekly. A figure of 12 weekly calls is perhaps more realistic for this port.

Table 2 also shows that the two terminals in Lisbon receive 29.5 ship calls per week. The total number of services mentioned in APL website for Sotagus, Liscont and TML indicates a higher figure of 34 services per week, including a small number of non-containerized general cargo services. The statistics of the port of Lisbon indicate that 1635 general cargo ships entered in the port of Lisbon in 2012, giving a weekly rate of 31.5 ships, a few of which are not containerships and are not regular services, a number therefore below 34 regular services. As a result, the number of ship calls at Sotagus and Liscont indicated in Table 2 may be considered as optimistic.

4 MARKET FORECAST FOR CONTAINER HANDLING

4.1 *Container throughput*

The development of a large container terminal is not worth the investment if there is no market for the infrastructure. The background outlined in the previous section needs to be taken in consideration in market forecast. The demand for container handling will depend on a first component related to the national economy and, in fact, also on Spanish economy if the hinterland of the port of Lisbon is to be extended so far. A second component will be an induced demand derived from the fact that a new transhipment terminal is added to the existing infra-structure. Both components have cross relations.

A new deep water terminal should therefore have an area dedicated to feeder services, so it should receive the existing services in Sotagus and Liscont. However, the number of such services calling at the new terminal is to be adjusted taking in consideration two aspects: existing services in Sotagus and Liscont might be duplicated and some rationalization might be needed, or in fact inevitable; the service's overall capacity needs to be adjusted according to forecasts for: a) future growth of container traffic demand (related to national economy), b) future growth of container traffic demand due to feedering containers to/from the larger deep sea services.

There should also be an area dedicated to larger vessels, Panamax and over, involved in deep-sea services. These vessels would partly be new to the port of Lisbon and size and number per week can be estimated from the numbers now calling at Terminal XXI, disregarding the below Panamax size vessels now calling at that terminal. A forecast is also necessary for the evolution over time of new deep sea services calling at an entirely new terminal. The experience gained from Terminal XXI can in this respect be taken into account.

The adopted methodology for the market forecast consists of starting with a forecast of the Portuguese economy (gross domestic product and exports) and evaluating the related increase in container traffic. It will be assumed that the container traffic will follow Portuguese exports closely without the negative impact from current labor problems in the existing terminals in Lisbon.

The traffic induced by the new transhipment terminal will then be added, with a certain schedule for bringing in line the deep sea services. It will be assumed that the impact of the terminal will be similar to Terminal XXI. It is then necessary to relate this forecast to the number and size of ships likely to call at both terminals, extrapolating from current number of services and container traffic, with impact on the "sea" side parameters of the terminal (quay length and depths). The time horizon of this forecasting will be 20 years.

Figure 7 shows the evolution of the number of boxes handled in Portuguese ports. It is worth noting the significant growth in boxes handled in Sines, which came from practically zero to almost 400,000 in eight years. Lisbon has stagnated and in 2012 shows a significant decline due to labor problems which have affected port operations.

Figure 8 shows the values of Portuguese exports and imports (includes all types of merchandises) and the accumulated number of boxes handled in Lisbon and Leixões. Note the closely similar pattern of the evolution of the total number of boxes handled in Lisbon and Leixões and the Portuguese exports. The correlation with imports is less evident because imports include a significant amount

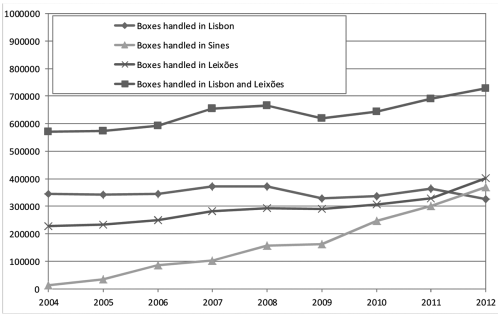

Figure 7. Evolution of number of handled boxes and Portuguese exports.

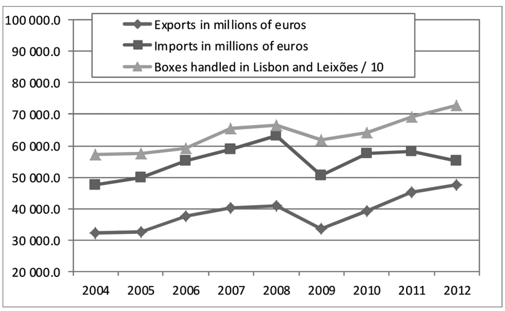

Figure 8. Evolution in boxes handled and exports.

of bulks, which are not carried as containerized cargo. The mentioned correlation with exports will be used to forecast the growth of container traffic from the forecasts for Portuguese exports published by different organizations.

Different forecasts in Portugal in the Autumn of 2013 predict growths in Portuguese exports for 2014 and 2015 of 4% to 5%. This may be assumed to translate itself into a growth in number of handled boxes in Lisbon at a more moderate pace of 2% to 5%. Two scenarios will be considered related to growths of 2% and 5%. The activity in the port of Lisbon in recent years has been hampered by labor problems, but it will be assumed that such problems could be overcome in the new proposed terminal and that the increase in traffic would follow that of Portuguese exports.

It will be assumed that the new terminal would come into operation in 2020. From then the transhipment traffic would follow a similar path to that experienced in Sines since 2004. It is accepted that this may be an optimistic scenario but the aim of this paper is not to produce a solid forecast of the expected developments but to use a forecast as one step to allow the application of the methodology for port design.

Here, different scenarios are considered regarding the period of time necessary to reach 500,000 additional boxes: 5 years or 10 years. After such period the growth in transhipment traffic will be 5%, a value in line with current predictions for Europe by Chiang (2013) for 2013–2017.

Figure 9 shows the result of the forecast for the number of boxes handled in the new terminal by adding both components, feeder and transhipment. It may be seen that by 2040, considering only the extrapolation of current traffic would produce a handling of nearly 600,000 boxes (2% growth). With a transhipment terminal added, growing at 5%, the number of handled boxes reaches 1,600,000. In number of TEU, these values equate to 900,000 and 2,400,000 TEU. It should be mentioned that world economy and shipping experience cycles of roughly 7 years, as shown in Stopford (2009), and therefore any forecast will certainly be affected by shipping cycles.

Figure 9 also shows forecasts made in 2007 for container traffic growth until 2025 and it may be seen that even the most conservative scenario is still quite optimistic in comparison with the known reality up until 2012. The conclusion is that the current forecast (2% growth on feeder and 5% on transhipment) is on the conservative side.

4.2 *Ship calls*

Taking in consideration the forecast above, the number and characteristics of the ships that might be expected in 2040 will be determined. That is, the traffic forecast will be translated into a demand for terminal quay length. Table 3 shows the estimate of ships in 2020 after the new terminal enters in operation. This estimate is similar to the sum of the ships now calling at Liscont and Sotagus.

Added to this are the ships which go into Terminal XXI. However, for this terminal, it is assumed that the feeder services existing in the Lisbon

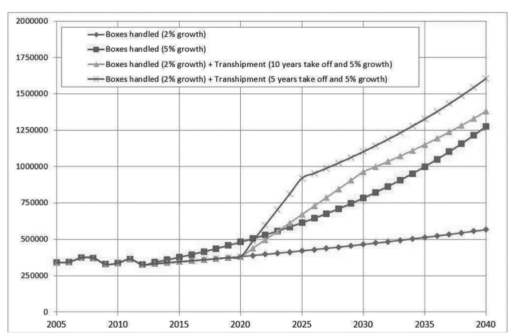

Figure 9. Forecasted growth in boxes handled in the new container terminal.

Table 3. Estimate of number of ship calls in 2020.

Sotagus type of traffic		Liscont type of traffic		Terminal XXI type of traffic	
450	2	200	2		
700	8	700	7		
2000	1	2000	7		
4500	0	4500	1		
				5500	3
				9000	1
				13000	1

Table 4. Estimate of number of ship calls in 2040.

Sotagus type of traffic		Liscont type of traffic		Terminal XXI type of traffic	
450	5	200	5		
700	18	700	16		
2000	2	2000	16		
4500	0	4500	2		
				5500	7
				9000	2
				13000	2

Table 5. Estimate of number of ship calls in 2040 (increased average size).

Sotagus type of traffic		Liscont type of traffic		Terminal XXI type of traffic	
450	0	200	0		
700	0	700	0		
2000	6	2000	12		
4500	2	4500	8		
				5500	7
				9000	2
				13000	2

terminals would be sufficient to take the role of the smaller ships in Terminal XXI that is of ships below 5500 TEU. This is assuming that the ships calling at Lisbon have the necessary overall free capacity to cover this increased demand. This assumption is realistic since the list of services published by the port of Lisbon is optimistic and some duplicated services exist. Overall, it is assumed that sufficient free capacity exists in the existing feeder network to support the new transhipment terminal.

The demand is now forecasted for 2040 taking in consideration that the terminal would then have to handle 2,400,000 TEU instead of the combined 1,050,000 TEU handled in 2012. Table 4 shows the estimate of the number of ships in 2040, assuming that the number of ships is proportional to the number of TEU handling.

However, it may reasonably be expected that the number of ships does not grow proportionally because there will be a trend towards larger ships. This would certainly happen for feeder ships but also for deep sea ships. Table 5 shows a re-arrangement of the traffic assuming that ships under 2,000 TEU capacity would disappear and their role would be taken over by ships of 2,000 TEU and over. The overall conclusion that the terminal will have to attend per week 18 ships of ~2,000 TEU, 17 ships of ~4,500–5,500 TEU and 4 ships of ~9,000–13,000 TEU.

5 METHODS FOR CALCULATING TERMINAL REQUIREMENTS

5.1 *Quay length requirements*

The number of berths necessary can be determined for each ship capacity and number of ships in Table 5 using the formulae (1) to (4). The total length of quay is calculated using formulae (5) and (6).

$$TEU_{mov} = f \cdot TEU_{tot} \cdot N_{ships} \tag{1}$$

$$T_{oper/week} = \frac{TEU_{mov}}{N_{gant} \cdot P_{gant}} \tag{2}$$

$$T_{oper/year} = 52 \cdot T_{oper/week} \tag{3}$$

$$N_{quay} = \frac{T_{oper/year}}{T_{avai}} \tag{4}$$

$$L_{quay} = L_{ship} N_{quay} \tag{5}$$

$$L_{quay\ total} = \sum_{i=1}^{N} L_{quayi} \tag{6}$$

where:

TEU_{mov} number of TEUs to be handled each week,
TEU_{tot} capacity of ship in number of TEUs,
N_{ships} number of ships of a certain size,
F fraction of ship capacity to be handled,
N_{gant}, P_{gant} number of gantries and productivity of gantries,
$T_{oper}/week$ required operation time per week,
$T_{oper}/year$ required operation time per year,
T_{avai} available time per year assuming operation 24 h per day, 7 days a week,
N_{quay} required number of quays,
L_{quayi} length of quay for given size of ship.

5.2 *Quay and yard requirements obtained using statistical method*

A database of modern container terminals was developed which includes 15 terminals in Europe (mainly in Spain, Germany and Holland), 1 terminal in Brasil and 5 terminals in Portugal (Sines, Lisboa, Leixões). The main characteristics of these terminals, as given by their operating companies, included in the database are: overall area, quay length, yard capacities and available quay and yard equipment. The objective of this database is to allow an empirical assessment of the required areas and equipment for a terminal of a certain handling capacity per year.

Figures 10 and 11 show the quay characteristics in relation to the TEU handling capacity.

Figures 12 and 13 show the main characteristics of the terminals in terms of total area and yard capacity. Figures 14 and 15 show the statistics for yard equipment.

It may be seen that there exists a substantial dispersion of the terminal characteristics as a function of TEU handling capacity, as a consequence of different types of equipment being used in the container yard, leading to different area requirements and different layouts. Also, the natural conditions

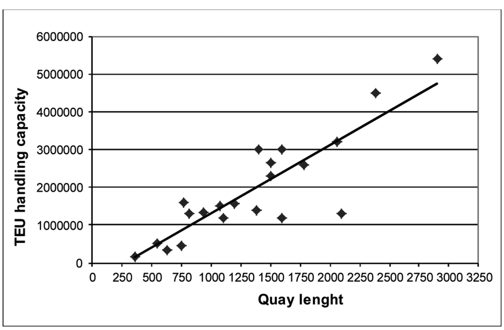

Figure 10. Quay length—Terminal handling capacity.

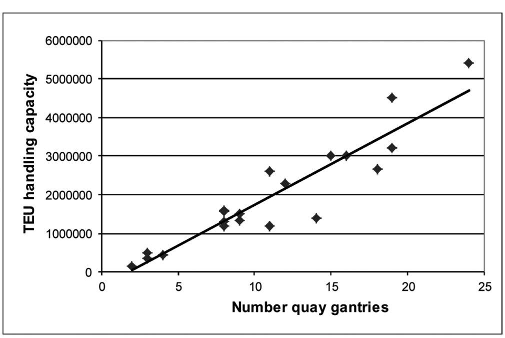

Figure 11. Number of quay gantries.

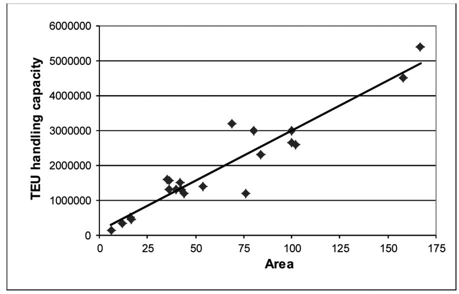

Figure 12. Total area.

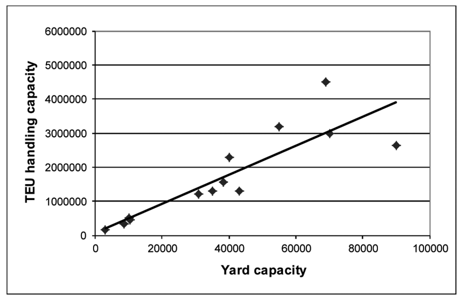

Figure 13. Yard geometrical capacity.

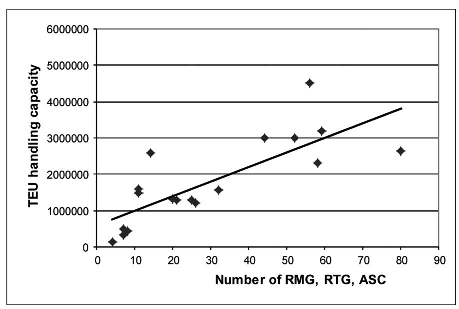

Figure 14. Number of RMG, RTG, ASC.

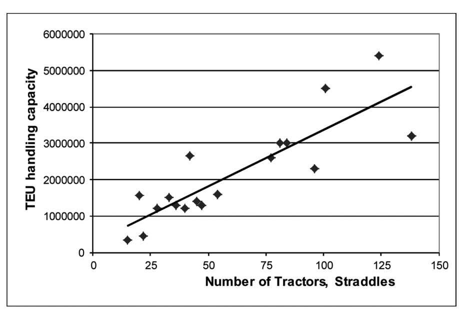

Figure 15. Number of tractors, straddles.

of each terminal and the type of ships received vary substantially, leading to further differences.

5.3 *Area and equipment requirements obtained using analytical methods*

A literature review showed two main analytical methods for pre-dimensioning container terminals: the one presented in the UNCTAD handbook on port development, see UNCTAD (1985), and the one presented in Thoresen (2003).

UNCTAD's handbook presents a comprehensive approach to port planning. Its chapter on container terminal planning provides guidelines and planning charts based on queuing theory for conducting the pre-dimensioning of a container terminal using the required terminal capacity, the expected traffic, type and efficiency of equipment and other parameters as inputs. Descriptions and limitations of several available container handling equipment are described. Even though this handbook has been published some years ago, it is still cited and its guidelines and calculation methods have been used in recent research, such as Guler (2001). It is to be noted that it does consider automated container terminals, because such technology is more recent, and that it is limited to the planning of terminals up to 400,000 TEU handled per year. Figure 16 shows some of the inputs and outputs of this method.

Thoresen (2003) presents a comprehensive approach to port planning, including guidelines for container terminals. However, unlike UNCTAD's manual, Thoresen provides analytical expressions for pre-dimensioning calculations of container terminals. Figure 17 shows some of the inputs and outputs of Thoresen's method, which is not limited to planning small or medium capacity terminals.

For example, Thoresen calculates the total required area as shown in formula (7).

$$A_T = \frac{C_{TEU} \times D \times A_{TEU} \times (1 + B_f)}{365 \times H \times N \times L \times S} \qquad (7)$$

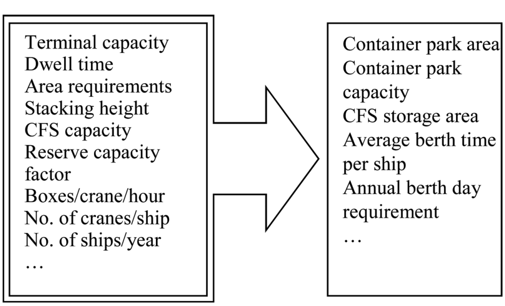

Figure 16. UNCTAD's inputs and outputs.

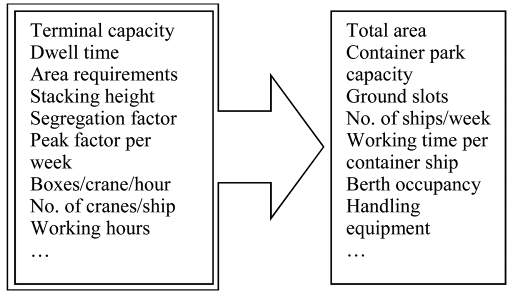

Figure 17. Thoresen's inputs and outputs.

where:
A_T total needed area,
C_{TEU} container movements per year,
D dwell time,
A_{TEU} area requirements per TEU,
B_f buffer storage factor in front of stacking area,
H ratio of average to maximum stacking height,
N container stacking area compared to total area,
L layout factor due to the terminal's shape,
S segregation factor due to different container destinations.

Other formulae are given for calculating container slots (yard capacity), containers handled per week for the design capacity, working time per container ship, STS cranes working hours, berth occupancy ratio.

The explanations of the two methods, charts and analytical expressions have been implemented computationally in a tool that calculates the container terminal characteristics for a given set of design parameters. For the UNCTAD's method, analytical expressions have been extracted from the method's explanation and through regression analysis, when needed. Also, extrapolations for off-chart values have been done when required. For Thoresen's method, the analytical expressions have been included directly.

5.4 *Validation of tool*

The comparison of numerical results of this tool with the statistical approach results and with the characteristics of phase I of Terminal XXI validating the tool and assess the methods implemented. Since the capacity of Terminal XXI in its first phase was 400,000 TEU/year, UNCTAD method is fully applicable.

Table 6 shows the results obtained using the different methods, along with the corresponding values for the statistical approach and Terminal XXI.

Table 6. Estimates for a 400000 TEU container terminal and comparison with benchmark values.

Characteristic	Terminal XXI (Phase I)	Statistical method	UNCTAD	Thoresen
Handling capacity (TEU)	400 000	400 000	400 000	400 000
Quay length (m)	380	500	–	–
Berths	1	–	2	2
Total area (ha)	18	17	15.39	14.98
Yard capacity (TEU)	–	10000	9 589	8 990
Ground slots (TEU)	2 880	2500	2 397	2 247
Number of quay cranes	3	3–4	6	6
Number of tractors	~18	15	–	18–30
Number of RTGs	3	8	–	12

It is to be noted that UNCTAD and Thoresen present different area requirements for the same type of handling equipment.

In order to make these method's outputs comparable, 10 m^2/TEU were used for both methods. This is a value between those given in Thoresen (2003) and UNCTAD (1985), which are respectively 12.5 m^2/TEU and 7.5 m^2/TEU, for yards equipped with RMG/RTG and stacks of 4 containers. It may be seen that UNCTAD and Thoresen methods are producing total areas of around 15ha and yard capacities 9000–9500 TEU. The area values are 2–3 ha below the values given by the statistical method and very slightly below the 10000 TEU yard capacity given by the statistical method. For Terminal XXI no values could be found for yard capacity but it can be estimated at 11500 TEU, in line with the higher terminal area (18 ha). The overall conclusion is that both methods are not far from the empirical evidence of existing terminals.

6 DEEP WATER TERMINAL IN LISBON

6.1 *Quay length and equipment requirements*

The method in section 5.1 is now used to calculate the quay length and equipment required for a terminal of 2,400,000 TEU.

Table 7 shows the results in number and length of berths obtained using the formulae in section 5.1, indicating that 2 berths for ships of 2000 TEU, 3 berths for ships of 4500–5500 TEU and 1 berth for ships of 9000–18000 TEU are necessary for the demand in Table 5. Overall, a quay length of 1760 m would be required. All berth lengths include margins of free space at the bow and stern. Assuming that the terminal works 7 days per week, as usual in these cases, this means that every berth receives one ship per day or slightly more for smaller ships. This is considered quite feasible since the average turnaround times are much smaller than 24 h and these depend anyway on the number of gantry cranes used. Table 7 also includes the required depths at different berths, ranging from 14.5 m to 18.5 m, depending on ship size.

Table 8 shows the number of gantries necessary to service the proposed berths, according with typical service patterns taken from the literature.

Smaller ships are serviced by 2 gantries (Panamax size). The medium sized ships are serviced typically by 3 gantries (post-Panamax size) and the largest vessels would require 6 gantries, at least if the 18000 TEU ships would be received. If only smaller vessels of 13000 TEU are expected, 4 gantries super-post-Panamax could be sufficient. Overall, a maximum of 16 gantries might be needed.

6.2 *Yard area and equipment requirements*

The database and tool developed and validated in sections 5.2 and 5.3 are now used to derive the yard and equipment characteristics for a deep water container terminal with a design throughput of 2,400,000 TEU.

Table 9 shows the general characteristics of such terminal. It may be seen that the quay length would be around 1760 m, the terminal area would be 75 ha, yard capacity 50000 TEU, 14 quay gantry cranes, 45 yard gantries and 75 tractors. Our estimates in the previous section indicated the need for 16 quay gantry cranes, value not too different from this. Thoresen indicates a larger area of 90 ha, a larger yard capacity of 54000 TEU and more quay cranes required. The yard equipment is however less numerous than that predicted from the database.

Table 9 also presents typical benchmark ratios generally used to assess the terminal characteristics. It may be seen that the ratios calculated with estimated terminal main characteristics (from statistics) are in line with benchmark values, except for RMG and tractor numbers which are slightly higher than usually found in this type of terminals.

Table 7. Estimate of quay length requirements in 2040 (increased average size).

Berths	Length (m)	Total length (m)	Length (m)	Total length (m)	Depth (m)
2 (2000 TEU)	220	440			14.5 m
3 (5500 TEU)	300	900			16.5 m
1 (18000 TEU)			440		18.5 m
		1340		440	
Total length				1760	

Table 8. Estimate of gantry requirements in 2040 (increased average size).

Number of berths	Number of gantries	Type of gantry	Number of berths	Number of gantries	Type of gantry
2	4	Panamax			
3	6	Post-Panamax			
			1	6	Super post-Panamax
Total	10			6	

Table 9. Estimate of terminal characteristics and comparison with benchmarks.

Characteristic	Statistics	Thoresen	Ratio	Benchmark
TEU handling capacity	2400000 TEU	2400000	–	–
Quay length	1760 m	–	1364 TEU/m	1200–1800 (1)
Area	75 ha	90 ha	30000 TEU/ha	20000–40000 (1)
Yard capacity	50000 TEU	54000 TEU	~833 TEU/ha	~800 (2) ~1000 (3)
Quay gantries	14	18	121 m/gantry	100–150 (from database)
RMG, RTG, ASC	45	36	~3.2 RTG/ gantry	2 (2) 2–3 (3)
Tractors, straddles	75	54	~5.4 Tractors/ gantry	3–5 (2) 4–5 (3)

(1) Wiese et al. (2009); (2) Thoresen (2003); (3) Bose (2011).

The TEU/yard area ratio is calculated with the stacking area, which considered to be 75% of the container terminal area.

Finally, taking in consideration that many containers will have to be taken to the north bank of the river, it is proposed to integrate the new container terminal with an inland container terminal for distribution of containers across the estuary of river Tagus. The quay and yard necessary for such terminal are not considered in the numbers given above.

7 CONCLUSIONS

This paper has presented a methodology for pre-planning container terminals which uses different methods to obtain the required characteristics of terminals for a given handling capacity. The first method is a statistical method, based on a database of existing container terminals, which allows determining the required quay and yard characteristics. For the quay length and equipment a method based on the profile of the ship calls is presented.

Calculation methods for quay and area characteristics have also been described and implemented. The results of these methods have been successfully compared and validated against the characteristics of an existing terminal.

The methods have then been applied in a case study, namely the basic design of a deep water container terminal in the port of Lisbon. This case study included a container traffic forecast up to 2040, providing an estimate of required throughput for the terminal of around 2,400,000 TEU. This value and the above methods were used to determine the approximate characteristics of the deep water terminal.

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Maritime transportation

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Maritime Technology and Engineering – Guedes Soares & Santos (Eds)

A generic maritime transportation network model

A. Carreira, J.P. Mendes & C. Guedes Soares
Centre for Marine Technology and Engineering (CENTEC), Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal

ABSTRACT: A network model, supported by a scalable and scope neutral model of the network agents, is introduced to model maritime transportation. This modelling approach can cope with the diversity of the entities involved in the transportation business and with the wide ranges in the scale and scope of the analysis domain and it supports the analysis of the competitiveness of container port terminals. Graph algebra can then be used to analyze port terminal competitiveness, which relates with the network robustness. A simple example model illustrates this procedure, exploiting full centrality and full intermediacy scenarios.

1 INTRODUCTION

Maritime container transportation can be characterized as an ensemble of agents that interact with each other, suggesting the idea of a network. These interactions originate new relationships and change the existing ones. This is the case of the relationship between shipping lines and terminal operators worldwide, whose outcome has had consequences in the shaping of maritime line networks, as analyzed in Parola & Musso (2007). Fremont (2007) illustrates this phenomenon with the particular case of the liner company Maersk, which privileges relationships with the terminal operator of its mother company (APM Terminals), avoiding ties with third party operators as much as possible.

In line with this, Notteboom & Rodrigue (2011) describe the worldwide tight web, composed of a small number of shipping firms, global stowage companies and financial societies that dominate the business of container terminal operations. The development of this network coincided with the container traffic evolution of the past decade, which, in turn, caused changes in the commercial attractiveness of ports (Yap et al., 2011).

This evolution of the relative importance of container ports is studied in Ducruet & Notteboom (2012). Here, a model of the world-wide container port network, based on the relationships between ports called by the same liner service, is setup for 1996 and for 2006. The analysis of this model relies on network theory elements, namely centrality indexes, and on the identification of nodal regions (Nystuen & Dacey, 1961), and reveals how ports and port regions have won or lost competitiveness in that 10 years period. Relying on descriptive and analytical methods, proactive approaches propose ways to improving the integration of ports in the worldwide logistics networks, like the case for Portuguese ports in Ortigão & Mendes (2010).

The networked nature of ports is highlighted in the concept of Port Community System, a port wide information system connecting all actors (shipping agents, authorities, terminal operators, etc.), described in Rodrigue et al. (2012). The port is portrayed as a gateway connecting the land and sea domains and it is considered that the foreland should be represented by the maritime transport line services, while the hinterland is better described by the logistics centers and related supply chains.

In spite of all the existing knowledge on this subject matter, which, in many occasions, invokes or uses network approaches, there is no comprehensive nor unifying network model aimed at the analysis of maritime container transportation, particularly on what concerns competitiveness and competitiveness factors. The issues faced when approaching the modelling of container transportation can be, at least in part, attributed to the diversity of agents—shippers, logistics centers, land modes transportation companies (road, rail, waterways), ports and container port terminals, shipping services and liner companies—not to mention the entities that operate inside, for instance, a port (port authority, pilotage, VTS, towing services, terminal operators, trailer services, railroad operators, etc.).

Any suitable modelling approach must accommodate the diversity of agents, in nature and in scale. The scope and depth of each instance of analysis also puts requirements in the granularity of the model and in the hierarchical representation and aggregation-disaggregation rules of the models.

Another line of research addresses the factors of port competitiveness. These are the properties that drive demand and correspond to a port's cargo moving capabilities, which are frequently labeled impedance factors. Dias et al. (2009) performed a benchmark of Iberian ports, looking into individual impedance factors to compare the differences in the ports' competitiveness. They built on the development of a comprehensive set of benchmarking factors in Antão et al. (2006). Caldeirinha (2010) relates port performance with "characterization factors", which correspond to the impedance factors, for a number of European ports.

The approach introduced here is based on a universal model of the agents, which addresses the requirements of agent variety and scale. The links between agents are the outcome of the competitiveness factors. This approach allows the building of models of transportation networks suitable for competitiveness analysis of any of its agents and overall network robustness.

The next two sections describe, respectively, the modelling of the network entities and the overall network model. These are then used to develop a simple generic maritime transportation network model, where the current and potential competitiveness of a container port terminal is analyzed.

2 ENTITIES OF THE NETWORK

An organization is an entity with a name and a stated purpose that interacts with other entities in its task environment (Thompson, 1967). Each entity is, in turn, a collection of agents, interacting internally, within the entity's boundaries, with some agents also interacting with agents of the other entities. This means that the interactions between entities are interactions between agents of those entities. The same happens inside organizations. For instance, a department or a business unit are themselves (sub) networks of agents, and interact with other networks, internal or external, through inter-agent transactions.

This network of entities-of-agents is captured in the Extended Enterprise Network (EEN) model described in Carreira et al. (2012).

At first sight, it seems reasonable to think of an EEN model as a representation at the functional level, where each agent corresponds to an organizational functional unit. However, the level of detail required to analyze a firm must depend on the objectives of the analysis. If a particular model is built at the functional level but the required level of analysis needs less detail, agent aggregation can be used to simplify the model.

The aggregation or condensation of agents presupposes well defined boundaries for each agent. That is, the definition of an agent must be complete and sufficient, as perceived by the other agents

- *Sufficiency* relates cause with outcome (a particular cause always produces that outcome) and *completeness* assures there are no other causes for that outcome (Rehder & Milovanovic, 2007).

The agent definition must also be consistent for all the agents in the network.

Whatever the level of detail, the entities being modeled perform tasks that require resources, communication and decision making capabilities. An agent of an EEN network model is, thus defined as an entity with decision-making and communication capabilities that performs actions using resources that are available to it. This definition considers an agent as an active entity and not just as a passive collection of attributes. The behaviors of the individual agents are, thus, embedded in the network model.

The modeling of EEN agents must handle elementary agents as well as agents resulting from the condensation of other agents. Regardless of the extension (scope) of its organizational representation, any agent must fulfill the definition above. Additionally, the iterative aggregation or disaggregation of any number of agents in a model, that is, the freedom to reset the granularity of the analysis in an EEN model, must keep the agent's boundaries, as implied in its definition. This must stand (a) for EEN models where all agents have the same representation scope and (b) for models where agents have different representation scopes.

Requirement (a) implies that the agents' modeling process must scale: in a network of high-level entities the modeling of the agents is performed the same way as in a network of low-level entities. Scalability is one of the two fundamental properties of the modeling of EEN agents.

Requirement (b) implies that the same modeling process is performed for agents with diverse representation scopes within the same network model.

This describes the second fundamental property of the modeling of EEN agents, which is neutrality of the scope of representation or scope neutrality.

It's worth noticing that scope neutrality requires scalability. As such, only scope neutrality is fundamental (sufficient condition) for the modeling of agents, as long as scalability is kept in mind as the necessary condition for that. However, for the sake of comprehensiveness both properties are made explicit in the approach to agents' modeling.

3 THE MANAGEMENT SYSTEM MODEL

The Management System Model (Kurstedt et al. 1988), or MSM for short, is a general descriptive model that allows for scalability and scope neutrality when modeling agents.

The MSM describes a domain of responsibility, or simply a domain, which "is the set of responsibilities of a decision maker bounded as a system". A domain is composed of three functionally independent elements (Fig. 1a). These are not always easy to isolate (the analogy of the physical computer and the information system it hosts may help understand this difficulty). The MSM makes explicit the balance of the three components (Fig. 1b).

The MSM does not meet the communications requirement in the agent's definition. However, the decision making process in the MSM implies the exchange of information with other agents (other MSMs). This becomes evident with the control loop analogue of the MSM (Fig. 1c), where the information is exchanged through the inputs and the output. The reference input includes the solicitations from the upper hierarchy and from peer agents (like a production order fulfillment request from sales or the instructions for unloading cargo from a ship), which, along with the output, represent the normal transactions. The disturbance input and the corresponding output may be seen as the exceptional interactions with the agent's environment, regardless of their type and frequency.

An important feature of the MSM is the capability to scope the definition of a domain of responsibility (agent) for each specific situation. A small-sized company, with just a manager (probably the owner) and some employees, each performing a specific set of activities, is a domain. However, a larger company with several departments (production, engineering, sales, finance, etc.), each with a manager, can be modeled as a network of individual domains of responsibility.

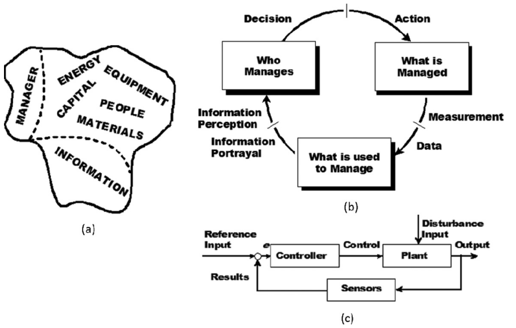

Figure 1. (a) The manager belongs in the management system. (b) The MSM makes explicit the balance of the three components. (c) The information exchange is evident in the control-loop analogue of the MSM. (adapted from Kurstedt et al., 1988).

Each domain is an agent described by a specific MSM. If required, some or all of the agents may be condensed into a single agent, up to one agent for the entire company, always exhibiting the same properties for the rest of the extended/external network. This process for defining the agent's boundaries, as required by the EEN model, can be scaled up or down at will.

It is easily perceivable that the MSM comprises the modeling of the enterprise management hierarchy, with the successive upper management levels becoming the front-ends of the organizations, following successive aggregations of lower-level agents.

Aggregation can still be extended to groups of organizations provided some precautions are taken, because the concept of "who manages" is not applicable. There are two main cases:

- **Case A**: Organizations are of different types. This is just the extension of the scalability and scope neutrality of the MSM model to a group of firms linked in a hierarchical way, where one of them has top authority (such as a Port Authority). A common example is a main contractor with a number of sub-contractors and suppliers dependent on him.
- **Case B**: Organizations are of the same type, providing the same kind of outputs and consuming the same kind of resources.

The aggregated outcome of the group can be modeled in the outcome of a single conceptual firm with a behavior equivalent to that of the group of firms, given the same (aggregated) inputs and outputs. These same type firms are, in one way or another, competing organizations, operating in the same market.

The "who manages" component of this abstract MSM does not really exist, but the group's behavior results from the composition of the interactions the organizations have with the market, which are affected by the feedback each firm gets from that market and from the actions it perceives being done by its competing peers. This agrees with the definition of MSM as illustrated in Figure 1 (c).

Case A and Case B MSMs can be aggregated recursively:

Case A MSMs can be obtained from the hierarchical combination of existing Case B MSMs,

Case B MSMs can be obtained from the aggregation of Case A MSMs.

4 EXTENDED ENTERPRISE NETWORK MODEL

Carreira et al., (2012) present empirical evidence suggesting that robustness in organizations can be explained by the networking effects of the Extended Enterprise Network (EEN). Network robustness is defined as the effort to break any of its links. Robustness of a system can also be defined as the capability to exhibit feature persistence under a disturbance (Jen, 2005). The two formulations can be seen as compatible and complementary because the capabilities of a networked system (its features) depend on its connectivity and on the stability of the connections. Robustness is, then, the outcome of the mechanisms that promote and keep the links of the network. In a EEN these mechanisms are the competitiveness factors, and network robustness becomes a measure of an organization's competitiveness.

The EEN model of an Organization Under Study (OUS) is realized by a graph whose vertices represent the agents of the OUS and the agents of the other organizations with which the OUS has a relationship. The graph's edges describe the interactions between the agents. Edges may be directed or undirected, but, in a particular model, all edges must be of the same type.

Edges are weighted to model the magnitude of the interactions. A zero weighted edge is equivalent to the absence of any form of direct interaction. The weight of the edge between vertices u and v, $w(u,v)$, is a function of meaningful variables that describe the links between agents, i.e., $w(u,v) = f_{uv}(x_1 \ldots x_g)$. The set $X = \{x_i: x_i \geq 0, i = 1 \ldots g\}$ is context-dependent and is defined for each specific network. The degree of a vertex is defined as $d(v) = \Sigma_u w(u,v)$.

All relationships in an EEN model are expressed in the same units. For instance, consider the EEN model of a maritime transport network describing the relationships between line services and ports. Using cargo volumes in TEUs requires all relationships to be expressed either in TEUs or in dimensionless units, normalized by sales or cargo. By the same token, the graph's edges of the EEN of a company that relates with others on the basis of buyer-seller relationships are weighted as a function of sales revenue, expressed in monetary units. Normalized dimensionless units can be used instead, with the normalization factor equal to total sales revenue. Relationships that do not have the same nature of sales or purchases, like taxes or dividends paid to shareholders, are also expressed in the same monetary or sales-normalized units.

Condensation of agents is realized by graph contraction, which consists of identifying two adjacent vertices, say. u and v, that may be elementary or result from previous contractions, and create a new vertex v^*, with the resulting edge weights given by (Chung, 1997)

$$w(x,v^*) = w(x,u) + w(x,v) \quad (1)$$

The contracted vertex has a self-loop, representing the interactions within and between the originating vertices, with weight

$$w(v^*,v^*) = w(u,u) + w(v,v) + w(x,v) \quad (2)$$

Graph contraction corresponds to condensing whole organizational units, parts of units or more than one unit into a single agent, represented by a vertex. The depth of analysis of an organization can, then, be performed at any level of aggregation and granularity, with all meaningful agents evidenced in the analysis. This originates a less populated yet clearer graph, more adequate for the purpose of the analysis (Fig. 2).

A Case A aggregated MSM represents a hierarchy of different MSMs. The corresponding contracted vertex has a self-loop that represents the compounding of the interactions in the hierarchy of firms and within each firm.

A Case B aggregated MSM represents a group of domains of the same type. The corresponding contracted vertex has a self-loop just to represent the sum of the interactions inside the individual organizations, because no direct interactions exist between them.

To study a network of organizations, each can either be contracted into single vertices or modeled by any number of vertices representing elementary or condensed agents. The environment of a specific firm can also be condensed. Beyond the representation of each outside organization by a single vertex, it is reasonable to consider contracting vertices representing external firms of the same type into a single vertex (a vertex for suppliers, a vertex for subcontractors, a vertex for customers, another for shareholders, banks, etc.).

Reciprocally, in cases where it is not possible or feasible to fully describe an organization or a set of organizations, by means of their internal agents, it may suffice to have one vertex per entity or per group of entities, like the set of customers of a particular type, with the correct edges weighting. Later, if required, one can refine the model in more

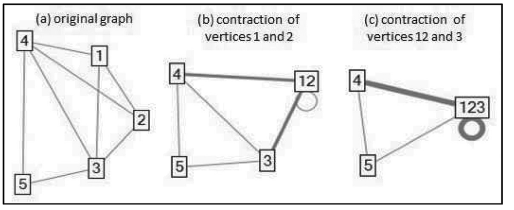

Figure 2. The contraction of a graph allows adjusting the detail of the network model (undirected graph with original unitary edge weights).

depth, by one or more levels, making the agents of specific organizations explicit. In general, a high-level vertex ought to include a self-loop to describe the interactions that take place within the (sub)network it represents.

This approach is useful when analyzing port networks. For example, the inherent complexity of a port, along with its counterparts, both inland and at the foreland, can be exploited at any level of detail. A port can be condensed into a unique agent if, for instance, the port is an entity of a maritime transport network being analyzed at the organization level, where it is more convenient to have one agent per shipper, one agent per inland logistic chain and one agent per port.

If the object of analysis is a multi-regional maritime transport network, each region can be modeled by condensing all its shippers into a single agent, all its inland logistics chains into another agent, and all its ports also into a single agent. Only the maritime services supporting the inter-regional trade need to be modeled, and this can be done with a unique vertex, with edges connecting it to the vertices representing the condensed ports. If the maritime services need to be studied in more detail, they can be represented by as much vertices as required (one vertex per service, if needed), while keeping the remaining of the graph with the same low detail.

The edge weights resulting from these contractions represent exchanges that describe inter-regional traffic between regions. For the analysis of the intra-regional trade of a specific region, an aggregation at the (lower) hinterland level may be adequate, condensing into single agents the entities of the same type in each hinterland—shippers, logistics chains and ports.

This rationale can be applied down to the lowest level, where each intervening elementary agent (like a stevedoring service) is modeled by a unique vertex and every individual relationship is assigned to a specific edge.

Agent disaggregation or expansion does not have a corresponding graph operation, because the inverse of graph contraction is not defined. This does not prevent the disaggregation of an agent into a meaningful (sub)network of more elementary agents, or the equivalent transformation of a vertex into a useful (sub)graph of connected vertices, by using adequate criteria, consistent for the whole network model. Obviously, edge weights must satisfy equations (1) and (2).

MSM-based EEN models, EEN-MSM models for short, can be developed with minimum data. Useful models can be based on relationships that are functions of a single variable, ultimately binary and just indicating whether or not agents are interconnected. Also, a lack of detailed data may require agents to represent entire organizations or groups of organizations, with the resulting model still providing sufficient analytical insight.

EEN-MSM models, are static and graph algebra can be used straightforwardly, namely spectral analysis. Network robustness is computed as the graph's algebraic connectivity, which is the second smallest eigenvalue of the Laplacian matrix of the graph, λ_1. The components of the corresponding eigenvector, the Fiedler vector, reveal the binary partition of the graph and show the first point of fragility (Fiedler, 1973, Spielman, 2004). In this analysis we use the random walk normalized variant of the Laplacian matrix (Luxburg, 2007).

When scaling up a model, by condensing agents, it is important to take notice that the resulting contracted graph may have a higher algebraic connectivity than the original one, and yet both represent the same network (Chung, 1997). i.e., if a graph $\boldsymbol{H}$ is formed by contractions from a graph $\boldsymbol{G}$, then

$$\lambda_{1H} \geq \lambda_{1G} \tag{3}$$

This means that the level of detail of a network should be kept for the entire process of analysis and that aggregation and disaggregation should be exercised with care, just to get the required analytical insight about the network behavior.

The simplicity of the EEN-MSM models allows the usage of other tools to enhance the analysis of a model, as long as the level of detail (aggregation) is not changed or if the tools are scalable and don't distort the scope neutrality of the MSM. For instance, the dynamic behavior of a network can be analyzed by using the appropriate tools to extend the MSM model to exhibit time-dependencies.

5 APPLICATION TO A GENERIC CONTAINER MARITIME TRANSPORT NETWORK

Consider the application of the combined EEN-MSM concept to a fictitious but generic maritime container transport network. The entities in this model represent all the intervening organizations in the different geographic regions encompassed by the network. These entities are better modeled by single agents, which enable a high level, low detail analysis, more adequate to understand such a wide scope network.

This network model permits a global view of the competitiveness of the ports in order to gather understanding of the overall phenomenon and to eventually specify forms of action to improve the competitive position of a particular terminal.

To further simplify the model analysis, the sets of entities that constitute the port's hinterland, i.e., shippers and logistics chains, can be condensed into a smaller number of agents, by type of entity. This can go up to a single agent per type of entity. Regional or overseas hinterlands can be modeled in this way, with an agent per type of entity. By the same token, shipping services may also be condensed. However, in this case, the condensation must not eliminate the visibility of maritime services with distinct routes. The agents' self-interactions are ignored because the model aims the comparison of a current situation with possible future outcomes resulting from Case B aggregations only, which do not originate new self-interactions.

The graph of a generic maritime container transport network is depicted in Figure 3.

The vertices labeled Shippers correspond to the agents that represent the cargo originators or receivers.

The vertices labeled Logcenters (logistics centers) correspond to the agents that represent the land-side logistics chains. These are served by the port terminals represented by agents whose corresponding vertices are labeled Port Terminals. The agents that correspond to the vertices labeled Shipping Services represent the regular liner services that call the ports.

The interest is in the competitiveness of port terminals and this particular model targets the competitiveness of Port 0, the Port Under Study (PUS). This port serves a hinterland also served by competing ports represented by Port 1. Port 3 represents the ports serving the other hinterlands of the PUS geographic region. Port 2 and Port 4 represent, say, two overseas regions that trade with the PUS region.

Shipping Services 1 and 3 stand for pendulum services between the overseas region represented by Port 2 and the PUS region. Shipping Service 4 stands for pendulum services between the PUS region and another faraway region represented by Port 4. Shipping Service 2 stands for the regional shipping services, basically short sea shipping, between the PUS and the rest of the region.

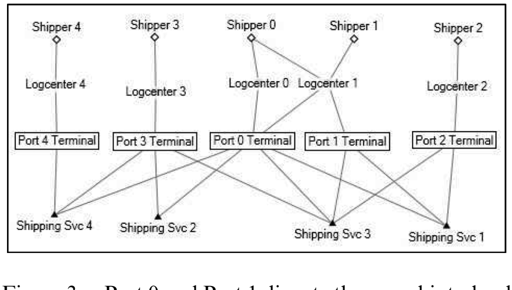

Figure 3. Port 0 and Port 1 dispute the same hinterland and serve the same geographic region with Port 3. Port 2 and Port 4 serve two overseas regions.

On the land-side, except for the PUS region and hinterland, each region is modeled simply by one shipper, representing all the cargo owners in the respective region, and one logcenter, representing the logistics chains in that same region.

Port 0 and Port 1 compete for the traffic in the PUS hinterland and also for any transshipping operations that target the traffic from/to Port 2, probably hub and spoke or relay destined to Port 3. Port 0 is also competing with Port 3 for transshipments aimed at traffic from/to Port 4.

An essential element of the competition between port terminals is their spatial relationship, which is described by several concepts (Slack et al., 2013). Two of them, originally identified in Fleming & Hayuth (1994), are of particular importance:

Centrality, which describes the port terminal as a point of origin/destination of traffic from/to neighboring economic regions

– *Intermediacy*, which describes the port as an intermediate point of traffic flows.

These concepts are further developed in Slack et al. (2013), which relates them with, respectively, the gateway and the transshipment functions in ports, and are used in this network model to represent the land-side and the sea-side competitiveness of port terminals.

The centrality of Port 0 is being challenged by the sharing of logistics chains (modeled as Logcenter 1) with Port 1 and by the fact that its natural shipper, Shipper 0, also uses Logcenter 1. And, in spite of being the only port in this network that is called by all the shipping services, the intermediacy of Port 0 is also limited by other regional ports being served by the same deep see shipping services that call it.

The limit situation for Port 0 is the following one

– Every logcenter connected to Port 0 has no connections with Port 1 and any transshipment taking place at this port is transferred to Port 0. Port 1 becomes useless and is no longer part of the transport network. This outcome is depicted in Figure 4.

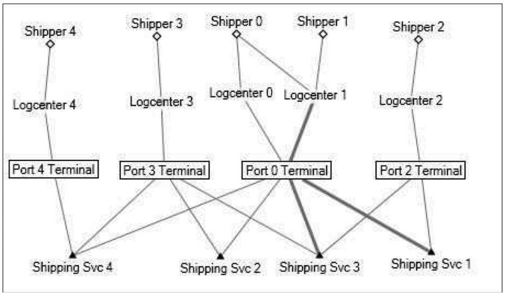

Figure 4. Port 0 achieves maximum centrality.

The weights of the edges previously incident to Port 1 have been redistributed by the links incident to Port 0, both in the hinterland and in the foreland. In this case, not only the centrality of the PUS is maximized, but also its intermediacy is enhanced. This may require improvement actions by the PUS to handle the new links.

– All deep sea shipping goes to Port 0 only and all foreland traffic is transshipped to the other ports of the PUS region (Port 3) as required, depicted in Figure 5. This is accomplished by a reinforcement of short sea shipping represented by Shipping Service 2.

This new situation of maximum intermediacy of Port 0 is the outcome of unilateral actions taken by this port. As such, the degrees of the vertices representing the other port terminals are not altered, and the same happens with the degrees of the vertices representing the shipping services. Vertex *Port 0 Terminal*, however, needs to increase its total degree, which may demand improvements in this port to handle the newly captured traffic.

The concepts of maximum centrality and maximum intermediacy conditions for a port are idealized, limit conditions and several intermediate situations might occur to improve Port 0's current competitive condition. Figures 4 and 5 illustrate such extreme conditions. It may appear that maximum intermediacy is associated with maximum centrality. However, if the PUS just longed for intermediacy, Port 1 might still be serving the hinterland, even if just feeding Port 0.

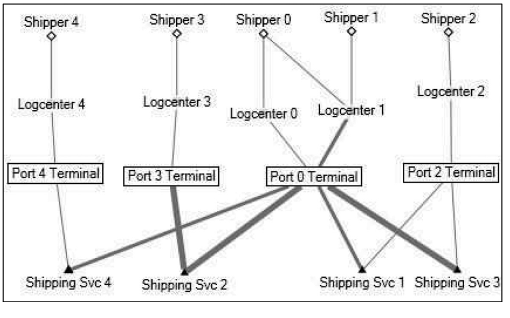

Figure 5. Port 0 achieves maximum intermediacy.

The edges weights of the original graph (Fig. 3) have been defined as unitary, because the purpose of this simple network is to introduce the modeling of maritime transportation networks. Yet, it is possible to compare the robustness of the original network with the robustness of the networks with maximum centrality and maximum intermediacy.

The algebraic connectivity of the original graph is $\lambda_1 = 0.099$. The modified graphs have slightly better equal algebraic connectivities: $\lambda_1 = 0.103$, meaning improved competitiveness, i.e., stronger and more stable connections. The increase in the robustness of the network with maximum centrality is explained by the suppression of the vertex *Port 1 Terminal*, and the merging of its edges with the edges incident on *Port 0 Terminal*. The degree of this vertex increases from 6 to 9. The graph now has fewer vertices for the same sum of the edges weights. This is algebraically equivalent to contracting vertex *Port 1 Terminal* with vertex *Port 0 Terminal* in accordance with equation (1), and checking equation (3).

The robustness of the maximum intermediacy network is an outcome of the increase in the edges weights of the *Port 0 Terminal* vertex, whose degree is now 13. The sea-side of this network has no meshes, in contrast with the two previous networks (Fig. 3 and Fig. 4). This loss of topological robustness is compensated by the strengthening of the links between the PUS and the shipping services.

The evolution in the degree of *Port 0 Terminal*, depicted in Table 1, is an indicator of the amount of improvement, requiring investment and additional operating costs, this terminal must undergo to achieve maximum competitiveness on the land-side and on the sea-side.

The set of weakest links, i.e. the cut set, of the original graph is

{(*Shipping Svc 2, Port 3 Terminal*),
(*Shipping Svc 3, Port 3 Terminal*),
(*Shipping Svc 4, Port 0 Terminal*)}.

This means that regional ports, represented by contracted vertex *Port 3 Terminal*, may link

Table 1. Port 0 terminal scenarios.

Scenario		MC* (Fig. 4)		MI** (Fig. 5)		
Degree *d*	Base (Fig. 3)	*d*MC	Δ *d*Base	*d*MI	Δ *d*MC	Δ *d*Base
Land-side	2	3	1	3	0	1
Sea-side	4	6	2	10	4	6
Total	6	9	3	13	4	7

* Maximum centrality; ** Maximum intermediacy.

preferentially with *Shipping Service 4*. However, care should be taken on interpreting this cut set because *Port 3 Terminal* represents a condensation of all the ports of the same region and a more detailed network model should be used to analyze this preference.

The cut sets of the modified graphs are

{(*Shipping Svc 4, Port 3 Terminal*), (*Shipping Svc 4, Port 0 Terminal*)}

for the graph of Figure 4, and

{(*Shipping Svc 4, Port 0 Terminal*)}

for the graph of Figure 5. The two networks apparently have a weaker link with overseas region 4, yet a better situation than the original one.

The analysis of this simple network sheds light on what is demanded to a port that wants to improve its competitive position in the transportation network. Such demand is put on the port's capabilities related to the links with the logistics chains in the hinterland and with the shipping services in the foreland.

6 CONCLUSION

The entities that encompass maritime container transportation and their relationships are captured in a network model, the Extended Enterprise Network. This model represents the agents that compose each entity and the inter-agents interactions, which materialize the institutional relationships between the entities and those internal to themselves. The entities are shippers, logistics chains, port terminals and shipping services. The diversity of the entities and of their agents and the scope of analysis that a particular EEN model must support requires a model of the agents that can scale and be scope neutral. The Management Systems Model is as suitable generic model for the agents, and allows the development of EEN models at whatever level of aggregation required.

The network, mapped into a graph, is analyzed for its robustness, an adequate measure of competitiveness, using graph algebra. This is applied to a simple Generic Maritime Container Transport Network whose purpose is to illustrate the applicability of the EEN-MSM modelling. A particular port terminal in the network is analyzed for its centrality (hinterland penetration) and intermediacy (transshipment strength). Idealized full centrality and full intermediacy scenarios are used to understand the robustness of the resulting networks, i.e., weather these limit situations correspond to a better competitiveness of the port under study. Robustness, measured by the graphs' algebraic connectivities, is always better in the new scenarios. However, these outcomes imply strengthening the links of the port under study, both for the land side and the sea side, for maximum centrality, and again on the sea side for maximum intermediacy. The required amount of improvement is a result of the network analysis.

The appropriate weighting function of the links and the amount of improvement required to increase the sea-side or the land-side competitiveness by pre-defined amounts, usually the result of a business plan, are topics for forthcoming research.

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Assessment of motorways of the sea through a method based on analysis of decision groups

A. Martínez-López & D. Pena-Agras
Department of Naval Engineering, University of A Coruña, Ferrol, Spain

A. Munín-Doce
Integrated Group for Engineering Research, Ferrol, Spain

ABSTRACT: Despite the European Union have favoured maritime traffic for years, through exceptions in the application of competition rules, in recent years these exceptions have disappeared progressively. Therefore, shipping companies have to adapt their service to the real needs of the shippers, identifying the controllable characteristics in their operational framework in order to act on them. Hence, this paper focuses on the introduction of a new hybrid model in multimodal transport, which allows the opportunity assessment for a shipping company, but through the decision criteria of the service user: the shipper. The results allow the identification of the main controllable and uncontrollable variables, constraints and objective functions for the shipping company, which condition the success of the multimodal chains from the shipper's perspective. This work develops a particular case to show this hybrid model: shipping companies considering, as a business strategy, to establish a motorway of the sea in Spain.

1 INTRODUCTION AND METHODOLOGY

The European Union (EU) transferred the responsibility for the development of multimodal transport to private companies from the administrations (Gesé & Baird, 2010), so shipping companies assumed the establishment of this kind of motorways. On the other hand, in recent years numerous studies, focused on the transport modal choice, were able to reflect the shipper's behaviour. However, their implementation in the classical approach to the opportunity analysis for the establishment of a motorway of the sea, integrated in a multimodal chain, has been hitherto practically inexistent from shipping companies' perspective. This paper aims to fill these gaps by offering a method of the opportunity assessment for a business strategy of a shipping company, but through the decision criteria of the service user (the shipper). Therefore, for the selection of the transport mode, we will used an explanatory hybrid model.

The evaluation of the business strategy for the establishment of a motorway of the sea can have the following stages: the analysis of the opportunity, the analysis of acceptability and finally the analysis of feasibility. The first one must provide a qualitative approach, evaluating the goodness level of its integration into the current framework and into the forecast scenarios. This qualitative evaluation allows the initial determination of the main variables, constraints and objective functions, which condition the potential success of the motorway, and therefore provide a first approach to the most suitable routes and fleets. Thus, this paper uniquely focuses on the opportunity assessment. The method proposed must be able not only to identify the main variables, but also to determine those that shipping companies can modified (controllable) and those that they cannot.

The transport sector allows high possibilities for differentiation due to its structural factors; essentially, due to this possibility, different transport modes can carry out the same service. For this reason, this work assumes that the differentiation of the transport company is the business's capacity to adapt its services to the real needs of clients (specialization focused on the shipper). Additionally, this work makes another assumption about the initial situation of the company: the business strategy (the establishment of a motorway of the sea) responds to the exploitation of a new transport service.

The competitive advantage of a transport company rises when it offers services with more attractive characteristics in cost and differentiation in relation to another business in the sector. In order to reach and to keep that advantage, the transport company should configure its services (strategic planning), integrating the decisions made from the evaluation of three areas:

- The service scope: market needs. Quantitative and qualitative analysis (Sapag 2001).
- The company scope: competitiveness and opportunities in front of competitors.
- The geographic scope: the scenario for service and technological needs.

Although the previous points may be valid for any sector, they are not sufficient for the transport sector because countries usually consider it as strategic in their economy; therefore, Government intervention is usually very relevant to transport activity. In fact, the transport regulation is responsible for the opportunity differentiation for many companies in this sector. Hence, it is necessary to include a new area in the evaluation:

- Regulation scope: trend and influence of the legislative framework in the sector.

The results achieved from the previous analysis (as in any decision process) lead to the identification of inputs: controllable (different options for projects) and uncontrollable (Sapag 2001). This work uses the previous process to configure the strategic planning of a transport company, but evaluating every scope from the point of view of the client: the shipper. Therefore, following this method, the client is the decision maker at every moment of the company strategic analysis.

Since the 1970s, the interest in the selection of the most suitable transport system for different cases has risen, and consequently many studies focused on this issue, especially ones that propose explanatory models (Mangan et al. 2001). Thus, previous authors determined different models: input models, output models, processing models (structural and sociological model). These previous models consider the application of different decision groups for the decision maker, in order to reach their aims.

The method proposed in this paper tries to take into account the majority of the decision groups, used in the previous models, but from a different perspective, since these decision groups influence the four evaluation areas of a transport company strategy. Thus, we call the provided method hybrid model, based on the evaluation of four different scopes, in terms of the following decision groups:

- *Activity requirements to assure competitiveness (ARC)*: cost and time are the main criteria to determine the costumer's decision about a transport system. In this group, the opportunity cost for the shipper is also considered.
- *Activity requirements according to load characteristics (ARL):* transport system should be suitable for load characteristics.
- *Activity requirements according to shipper needs (ARN):* it is necessary to specify transport requirements, such as the expected minimum frequency among means of transport, according to the shipper needs. The kind of route covered by the transport system is another requirement that must be included in this group.
- *Activity requirements according to the space–time context (ARX):* these characteristics take into account the political and legislative framework. This framework often determines the transport operation and its development in the market.

The method finally defines the variables that are not controllable by shipping companies, which can be sorted as: static results (SR), belonging to the operational framework (port facilities and geographical feature among others), and dynamic results (DR), which can change with time due to temporary economic conditions and business strategy of competitors. Finally, the results, that are controllable by the company (CR), are technical and operational characteristics, that may vary depending on the design and operation of the transport system. From the analysis of these variables, it is also possible to identify the need objective functions and restrictions (from a qualitative point of view), which condition the success of a motorway of the sea. Due to the importance of the multimodal transport for peripheral countries, this paper proposes the evaluation of introducing a Short Sea Shipping (SSS) service with a motorway of the sea from Spain, using the hybrid model.

2 THE EXPORT/IMPORT MARKET IN SPAIN: QUANTITATIVE AND QUALITATIVE ANALYSIS

First, it is important to evaluate the commercial flows to establish a possible transport route (ARN). Spain carried out in 2009 over a half of its commercial exchange within the EU. France and Germany are the main customers and suppliers, as shown in Table 1. In order to identify the

Table 1. Distribution of the total volume of Spanish foreign trade from January to December 2009 (Ministry of Industry, 2009a).

	Export flows to (%)	Import flows from (%)
EU		
France	19.34	11.71
Germany	11.07	13.43
Italy	8.17	7.24
Rest of UE	12.10	10.64
Total UE	69.11	58.01
Rest of Europe	6.40	6.23
North America	4.02	4.50
Latin America	4.74	4.68
Asia	7.03	17.74
Africa	5.82	8.06

Table 2. Spanish export trade by sector and producer company size.

Economic sectors	Products	% Total export flow	Produced by export companies: % Small and medium
Equipment goods	Agricultural and industrial machinery	1.26	69.70
	Office machines	1.03	56.30
	Other transport material	1.09	60.70
Food manufacturing	Meat industry	0.98	68.50
	Food products and tobacco	0.85	58.50
	Drinks	1.16	68.70
Chemical manufacturing	Chemical products (organic and non-organic)	1.35	55.60
	Plastics	1.23	77.80
Consumption manufacturing	Textile industry	0.94	79.50
	Leather and shoes	1.00	91.00
Non-perishable goods	Furniture industry	0.87	76.80
Weight of studied sectors in the total Spanish export flow in 2009 (%)			62.30
Weight of SMEs' production in the total export flow in Spain 2009 (%)			41.12

possible users of a multimodal transport system, it is interesting to bear in mind that the European business net is built on small and medium-sized enterprises (SMEs), which constitute 20.8 million (private and non-financial) entities as compared with 43,000 large enterprises (according to the Annual Report on EU SMEs 2010/11, European Commission).

Thus, the international commercial activity of SMEs is a great challenge for European economic policy. The Spanish SMEs represent the largest number of Spanish exporter companies (67.9% in 2007), and export the largest volume of products (Tab. 2, Ministry of Industry, 2009b), exporting goods to the value of over 100,000 euros per year (53.42%). Due to this, SMEs are the most interesting users of a transport service from Spain, and the most probable destination of the Spanish load is France.

Product features often determine the transport system selection (ARL). Thus, having identified SMEs as potential clients for a multimodal transport service, it is necessary to take into account the economic sectors to which their products belong.

Table 2 shows the distribution of products, grouped by economic sector. As can be seen in this table, SMEs exported 41.12% of the total exported volume in Spain in 2009, and their products belonged to the Spanish most important economic sectors. In addition, a multimodal system can transport any of their products.

3 THE COMPANY: TRANSPORT SYSTEM ALTERNATIVES

3.1 *Shipper characteristics*

Traditionally, SMEs with international activity used road transport to cover their logistical needs, because this system adjusted to their competitive model. The main SME transport requirements define the ARL decision group. Those are high frequency of sending and receiving goods, 'door-to-door' service and appropriate size of the transport system for small volumes of different kinds of loads. However, the trend towards association has been very remarkable in recent years (ARN). Because of this, the creation of clusters and consortiums of SMEs has appeared as a strategy to improve the transport conditions offered to them. Within this tendency, a multimodal maritime transport system arises as a real alternative to road transport for the transportation of small volumes with high frequency. In addition to the favourable effects of business association (ARN), it is important to note that the gregarious location of the SMEs also allows them to take advantage of logistic synergies and to centralize the transport demand (SMEs tend to establish themselves around industrial centres). Despite this, SMEs do not benefit from the effects of economy of scale, so they must minimize the cost attributable to the load. To this end, it is necessary to maximize the occupancy ratio in the transport system.

3.2 *Opportunities for the multimodal system*

Road transport was the system used by more than 83% of the goods exchanged between Spain and France in 2008 (INE 2008). Due to this, the competitiveness between road transport and multimodal transport must be analysed (ARC), in order to determine its strong and weak points. This analysis evaluates two main features of transport operation (Mangan et al., 2001): the transport cost for users and their opportunity cost in terms of time (ARC).

The gap between the shipper sending its commodities and unloading them at their destination will be the total transit time. Therefore, this time is a critical parameter for every kind of sector and goods for SMEs. The average speed and transit continuity influence the time. The first point is limited for road but not for maritime transport. Despite congestion situations in road traffic, loss of time at the port and low fluid connections, between the different means of transportation, give road transport an advantage regarding transit continuity. In fact, time is a recognized weak point for the competitiveness of the multimodal system (Olivella et al. 2004, García-Ménendez & Feo-Valero 2009). Nevertheless, EU regulation is balancing this point as we explain in Section 6.

The transport cost has a very important bearing on the total cost of every metric ton produced by SMEs as they transport small volumes. Despite the fact that maritime transport has turned out to be the most energy-efficient alternative (White Transport Paper 2001) for multimodal transport, it is necessary to add the goods transportation cost by land to maritime traffic costs. In order to balance the favourable situation of road transport regarding costs, the EU member states have applied a payment policy to road transport and tried to reduce the port costs for ships covering regular lines between European ports (Reform of the White Paper 2006). In addition to this, in many cases, the average distance travelled through multimodal transport is less than that travelled by road; hence, this point should be favourable to the multimodal system.

4 ROUTE SELECTION

This section carried out the port selection to establish a maritime route in an intermodal chain, considering the relative situation of intermodal transport regarding other competitors (ARC). The EMMA study concluded that the optimal maritime distances for using SSS are between 500 and 1400 km (ARN). Afterwards, in 1999, the Communication 'Development of the short sea shipping in Europe' established that the most interesting average distance for SSS (origin–destination) was 1385 km. In 2004, the INECEU Project concluded that from Spain the minimum maritime distance to achieve SSS effectiveness was 834 km.

The results achieved in this project also showed that, as the studied ports are closer to the Pyrenees, road transport emerged as the best choice, especially regarding time. Nevertheless, in ports on the Spanish north coast, the farthest from the Pyrenees, the difference in time between the two transport systems (maritime and road system) was not too large. Finally, it is worth mentioning that the WEST-MoS Project (2008) concluded that the average distance through the Pyrenees was 1371 km (ARN), in order to ensure the competitiveness of multimodal transport. Taking into account all the previous points, the Spanish ports selected for the study were (ARC) Gijón, A Coruña and Vigo.

These ports are ends of routes in Spain due to the features of their hinterlands (Garcia-Alonso & Sánchez-Soriano 2010). On the other hand, the final destination of goods are French cities, according to the possible routes (Tab. 3), because the main population centres are also the main consumption centres for SMEs' products. However, you can only reach Paris, Lille and Rennes through the Atlantic coast. Therefore, the French ports selected are Calais, Le Havre and St. Nazaire, because they are the most suitable to reach the mentioned cities, and they move the highest volumes of general load on the French Atlantic coast. According to Table 3, and with the exception of Gijón–Rennes, road distances are about 1385 km, which is the recommended distance for using SSS. Regarding the maritime routes recommendation (834–1400 km), Vigo is suitable for every possible French port; St. Nazaire does not meet this requirement in the case of A Coruña and Gijón (ARN).

Accordingly, the previous results, based on distance, are not sufficient to make a decision about the best maritime route with which to establish a multimodal transport system. It is necessary to carry out a new evaluation in terms of competitiveness (ARC). The comparison of the multimodal chain (stretch by land and by sea), with regard to road system, were carried out in relation to time and cost. To this end, speeds of 80 km/h on regular roads and 90 km/h on motorways (ED 92/24/CE, 92/6/CE) were considered in the case of road transport. Additionally, this works evaluated two operational possibilities: a maximum of 9 hours per driving day and continuous driving, with different drivers observing the compulsory breaks. For maritime voyages, a speed of 30 kn for ferries of 157 trucks and a load/unload speed of 34 trucks/hour (Authority of Vigo Port) were taken. The vessel speed could be considered too bold; however,

Table 3. Distance of Atlantic routes between Spain and France (km).

Spanish ports	French ports	Distance	French cities	Road distance
Vigo	Calais	1390	Rennes	1453
	St. Nazaire	915	Paris	1577
	Le Havre	1232	Lille	1793
A Coruña	Calais	1225	Rennes	1392
	St. Nazaire	735	Paris	1514
	Le Havre	1067	Lille	1731
Gijón	Calais	1138	Rennes	1061
	St. Nazaire	563	Paris	1184
	Le Havre	980	Lille	1400

the WEST-MoS Project estimated an effective speed of 28 kn for ships covering the minimum frequency required for SSS to be economically sustainable. The INECEU Project kept the same idea, and even other studies presented high-speed crafts as an option for this kind of traffic (SPIN-HSV Study 2004).

Neither the difference in cost savings nor the difference in time increases was wide enough to select a Spanish port as the optimal departure port (ARCs are not deciding factors). Hence, it is necessary to apply another criterion: the nature of the goods (ARL). Therefore, this work considers loaded and unloaded goods in Spanish ports and their potential market. Despite the fact that other studies about ports competitiveness have used different decision makers (García-Alonso & Sánchez-Soriano 2010), in our hybrid model, the load producer was assumed as the unique decision maker.

Table 4 shows Vigo as the port with the largest exchange of general goods. It also moves the largest quantity of goods in containers (a necessary characteristic of SMEs' load). Consequently, the port selected as the Spanish reference port was Vigo. Due to maritime transport is a part of intermodal transport, the influence of loading/unloading operations in port are included, in order to ascertain the advantages of using port facilities (ARL). Many previous studies concluded that, in terms of time, the use of port facilities for containers is more efficient in Europe (González & Trujillo 2008) than using the vessel's facilities. However, the influence of technical advances in this field was not as important as expected in Spanish ports and the average efficiency was 91.9% (González & Trujillo 2008). Analysing the port hinterlands of the selected French ports, the following characteristics are remarkable:

St. Nazaire is the nearest port to the Rennes area. The distance Nantes–Paris is greater than the distance from the port of Le Havre but St. Nazaire is a good option for the intermodal chain as the total time invested is shorter.

Le Havre port establishes a very important route from Vigo due to its great proximity to Paris. This maritime route also reaches Lille.

Calais is an interesting port for import and export flows with Belgium and United Kingdom from Spain. In addition, the French hinterland of Calais port spreads out to Lille, or even to Paris.

Within a radius of 300 km (ARN) around Vigo, there are more than 220 SME centres in Spain and in the north of Portugal, down to Porto. Therefore, there is a load potential of Vigo port hinterland towards France.

Table 4. Volume of general goods and containers, exported and imported in 2009 (tons).

	Total	Container
Coruña	1 444 840	123 724
Gijón	587 401	175 016
Vigo	2 607 037	1 582 047

5 FLEET SELECTION

According to the potential market detected (SMEs), the current situation of the studied ports and load nature, containers or trailers (ARL) are suitable.

This is due to the necessity of moving small volumes of very different goods. The kinds of load, vessel and facilities used are mainly responsible for loading and unloading operations costs (ARL). For the case of SSS, the shipping company assumes these costs and they are included in the freight cargo. 'Rules for the Motorway of the sea between Spain and France' (BOE No 265 2006) were consulted to determine the minimum cargo needs for vessels. The requirement was a minimum amount of cargo units (containers or trucks) of 221 per day and direction independently of the kind of vessel used.

Additionally, as seen before, it is necessary to maintain a minimum vessel speed of 30 kn to ensure the competitiveness of multimodal transport. It is also important to avoid the high-speed craft condition, as it introduces many operative restrictions (SPIN-HSV Study 2004). Both requirements apply to vessels of a minimum length of 100 m. Vessels of 150 m in length operating at 35 kn would not reach the condition of high-speed craft (MSC 36(63), SOLAS, Chap. X); therefore, these two alternatives will be studied. All the studied ports have available infrastructures to offer a cargo handling service for a ro-ro cargo (ARL), and enough equipment for load operations of containerized goods, with the exception of Calais. The load speed considered for the operation with ship cranes (2 per vessel of 100 m in length and 3 for 150 m in length) is as follows:

$$\textit{Rate per ship crane} = 13\ \textit{containers/h} \quad (1)$$

The alternative of using port cargo handling equipment means initial savings in shipbuilding cost, compared with another alternative, but, as a disadvantage, this option implies large dependence on ports' facilities (ARN) and efficiency (ARL). The load speed for port cranes was:

$$\textit{Rate per port crane} = 27\ \textit{containers/h} \quad (2)$$

The following equation applies to the time invested in cargo operation for trucks without a tractor unit (Ametller 2007):

$$Rate = 8\ trucks/h \cdot driver \tag{3}$$

The time invested in the trucks load with a tractor unit, using port drivers is expressed (State Stowage Society of Vigo Port) as:

$$Drivers = trucks/45 \tag{4}$$

For both kinds of cargo units, the fastest mode is to use port facilities. Therefore, this work considers these options for calculating the possible fleets. On the other hand, the kind of ship mainly determines the ship costs (ARL). They consist of port dues, port services and costs of the representation agency of the shipping company in port. According to load nature (ARL), the following ship types are suitable for containerized or rolling goods: roll-on roll-off ship (RO-RO), mixed ship: RO-RO and container (CONRO) and container ship. In order to meet the previous requirements, it is necessary a RO-RO fleet of two vessels (in each direction) of 150 m in length (153 trucks), operating at 35 kn, or 3 vessels of 100 m in length (85 trailers) at 30 kn.

CON-RO ships make better use of the available space in the cargo hold. The possible fleets (in both directions considering cargo port facilities) are two vessels of 100 m in length (42 trailers and 133 TEUs); due to time restriction, the total time invested in the maritime stretch is higher than 24 h considering the port facilities. Alternatively, two vessels of 150 m in length (59 trailers and 716 TEUs) due to the cargo restriction.

The container ship optimizes the unitary space for the load (ARC) and its structure is the least complicated; therefore, the initial investment in the ship is lower. In this case, the fleet would consist of two vessels of 100 m in length (237 TEUs) or two vessels of 150 m in length (1200 TEUs).

6 TRANSPORT REGULATIONS

Regulations apply to this sector strongly determine the transport system selection. Therefore, the decision group of activity requirements, according to space–time context (ARX), will exert a large influence on the opportunities for ship owners and shippers. From the policy trend analysis, we can conclude that the EU protectionism over maritime transport has lightened over the years. Firstly, the Code of Conduct on Maritime Conferences established the distribution of cargo tons proportionally between conference members. Afterwards, Regulation 4056/86 allowed a system of exceptions by categories, establishing the access to maritime traffic competition. Finally, Regulation 1/2003 abolished all the exceptions, excluding 'tramp traffic' and coastal navigation. The main consequence of the sector deregulation is the increase in competitiveness among shipping companies, and therefore the service price decrease, which benefits the multimodal transport system's competitiveness.

With the purpose of freeing European roads from the large amount of traffic, the EU has decided to boost SSS as a serious alternative to the road transport system (since the publication of the first White Paper in 1992). Among the main drawbacks detected for the development of SSS were the administrative complexity and customs formalities. These were resolved through Directive 2002/6/CE (which established the use of FAL Convention work forms in all member countries). With the purpose of improving port efficiency, the EU has encouraged private initiatives in port services. The main lines address towards deregulating the stowage business, in order to encourage competition.

In 2006, EU published a study on motorways of the sea opportunities, carried out by the Coordination Platform for Maritime Transport (Atlantic Transnational Network 2006) within the VI Framework Programme. This study stated that there was a great projection between the central French coast and ports of the north of Spain, both for RO-RO traffic and for container traffic. This conclusion reinforced the previous objective of developing the Western European motorway of the sea before 2020 (included in the N21 Project 2009), which would connect Spain and Portugal with the Irish Sea and the North Sea through France (ARN). Consequently, France and Spain signed, in October 2005, a collaboration agreement ('Declaration of Intentions about Motorways of the sea'), for selecting proposed projects on motorway of the sea between the two countries. Notwithstanding the public financing for these projects, the requirements for liner services are quite demanding. In fact, this agreement demands a minimum movement of 350,000 semitrailers (ARL) in the first 5 years between the two affected countries, and a minimum frequency of 4 voyages in each direction per week, during the first 2 years (221 cargo units moved in each direction). This boosted a favourable rule atmosphere for shipping companies (ARC) that operate between Spain and France.

7 CONCLUSION

From an academic perspective, the paper contributes to the multimodal transport literature by proposing a method that addresses the opportunity assessment of a motorway of the sea, integrated into a multimodal chain, in order to adapt the shipping company service for the real shipper needs. The proposed methodology applied a set of scopes, in accordance with a hybrid model, built on conclusions extracted from different decision groups based on shipper's criteria. This work sorted the results according to the possibilities of the company to act on them, and those that determine the strategy suitability to the circumstances and market tendency. The following paragraphs show all of them.

No controllable results: Static results (SR):
The transit time in the intermodal system is a disadvantage for multimodal transport. The European transport policy is trying to minimize this problem through the standardization of customs formalities for maritime transport, and the introduction of deregulated load and unload services among others.

The most important characteristics of a transportation service for SMEs are small and medium volumes of load with a high frequency of sending in a 'door-to-door' service.

EU is still committed to private enterprise as responsible for establishing and operating competitive motorways of the sea. This requires ship owners to enhance the optimization of their resources and rethink their competitive position in the market.

Transport attributes that clearly determine the modal decision are time and cost, the difference maximization from the main competitor in transport is the goal to pursue.

The Spanish ports, selected to operate with French ports, in terms of operational versatility and recommended distances, were A Coruña, Gijón and Vigo.

Vigo port, as the extreme of the routes studied, would allow SMEs to operate in a radius of 300 km (Spain and Portugal) with multimodal transport, with the same time and cost as road transport.

Calais port poses an operative constraint due to its lack of cargo handling system for containers.

All the studied ports have the infrastructure required to provide a motorway of the sea (berths of 200 m and loading ramps for RO-RO). Given the characteristics of these ports, the ship size that would maximize the operational flexibility would be 100 m in length and depth not exceeding 7 m. With these dimensions, the ship can expect to avoid waiting times at port.

No controllable results: Dynamic results (DR):
The trend towards globalization and the shortened life cycles of products require SMEs to establish international activity. SMEs' size and importance is growing in Spanish foreign markets. This identifies SMEs as a target charger for multimodal transport.

The main customer and sending country for Spanish foreign freight is France.

Once the transport system is suitable for SMEs, costs and time become critical factors to assure the transport system's competitiveness. Consortiums among shippers lead to better cargo space use and good unitary cost minimization.

The French cities selected as route ends were those with the most populated metropolitan areas, and the selected French ports were those whose geographical position and importance in the French port system were relevant (Fig. 1).

Finally, Vigo port was selected as the Spanish port in this research (Fig. 1), due to having the largest quantity of container freight movement; therefore, it presented the best prospects for attracting container cargo, in spite of the fact that it was not the best placed in terms of time.

Controllable results (CR):
The vessels' adaptation to port demands and to the routes at a high operation's speed (without reaching the category of 'high-speed craft') could resolve the intermodal system delay time versus road transport.

To meet the motorway of the sea requirements between Spain and France, it will be necessary to provide at least three container ships of 100 m in length. If larger ships are used to this end, these will be able to operate at a higher speed (without considering them as 'high-speed craft'). The use of smaller ships implies a reduction in their operational speed and, therefore, their competitiveness; for this reason, we ruled out this option. Therefore, the vessel speed and the number of ships will be other controllable variables to define.

The studied routes (Fig. 1) were the shortest in distance, articulating each chain a 'one-to-one' model. Although all of them complied with the rec-

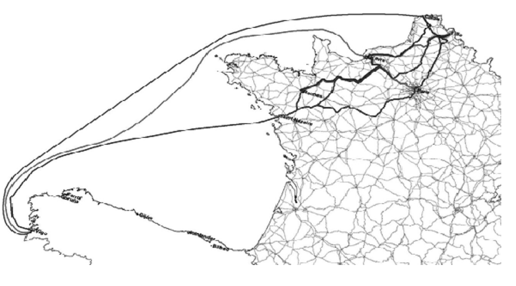

Figure 1. Multimodal routes from Vigo port to Lille, Paris and Rennes through the French ports of St. Nazaire, Le Havre and Calais.

ommended distances in previous studies, this distance was the most important selection parameter, and it would be necessary to choose the maritime route taking into consideration burden distribution between different destinations in France ('one-to-many' or 'many-to-many' models). Therefore, the selection of a single route between two ports will be an important variable to set.

The multimodal chain's competitiveness in terms of cost links to the port charges, which depend primarily on the vessels' features (auxiliary variables: length between perpendiculars, tonnage, etc.). These features depends on the type of vessel, type and amount of cargo units, manoeuvring means and selected cargo handling systems. Vessels suitable for cargo transport were containers, RO-ROs and CON-ROS.

Based on the uncontrollable results (SR and DR), it is appropriate to accept that the establishment of a motorway of the sea between Spain and France is a favourable opportunity, as it adapts to the environment needs and studied context tendency. Despite this fact, it will be necessary to take decisions about the fleet, the route and the client, in order to optimize this opportunity. For this reason, this work qualitatively defines some objective functions, key variables that influence the achievement of these objectives, their relationships and their constraints. These decisions directly influence the acceptability of the business strategy and therefore different cases and alternatives should be analysed in a further study.

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Competition dynamics between the Hamburg-Le Havre and the Mediterranean port ranges

A.M.P. Santos & C. Guedes Soares
Centre for Marine Technology and Engineering (CENTEC), Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal

ABSTRACT: The dynamics of port competition between the Hamburg-Le Havre and the Mediterranean port ranges is addressed with a systems approach. Causal relationships between variables are derived from published relevant literature and represented by means of causal loop diagrams. Given their appropriateness, a set of systems archetypes is used to explain the observed system's behavior. Afterwards, the obtained causal loop diagram is translated into a set of ordinary differential equations from which a simulation model is constructed. The obtained model's structure and simulation results show that the insertion of pure regional transshipment hubs is not a fundamental or long-term solution to increase port range competitiveness. Instead, the proposed model supports the notion that long term improvement of market share can only be obtained through a port regionalization process, directly entwined with the development of hinterland accessibility and an increase in gateway traffic.

1 INTRODUCTION

Port competition can be analyzed, at least, from three different perspectives: competition between port actors within the same port; competition between individual ports; and, increasingly, between port ranges, particularly where there is hinterland overlapping. Additionally, in recent years, competition has evolved from one between individual ports to one between entire supply chains in such a way that for a port to succeed it must be part of an efficient supply chain (Meersman et al. 2010).

While intra-port competition is determined mainly by factors of production such as capital, labor and technology, at a broader level, where competition is between ports or port ranges, regional factors, such as the geographical location and hinterland accessibility, play a decisive role.

The focus of this paper is on competition between port ranges with partially overlapping hinterlands. In particular, competition between the Northern and the Mediterranean ranges will be addressed. But before moving forward, a definition of what is meant by 'hinterland' is necessary.

To date, no single metrics for outlining an hinterland's extension has been agreed upon, and most often loose definitions are used, such as that of Notteboom (2008) who defines hinterland as "… the area over which a port draws the majority of its business". The fact that a port usually has different hinterlands for different commodities and the notions of 'captive' and 'contestable' hinterlands further difficult reaching a unified hinterland definition.

Nonetheless, and no matter what the definition used, it is commonly agreed upon that containerization has extended the gateway ports' geographical reach (OECD/ITF 2009). An important consequence of this is the increasing overlapping of ports' hinterlands and the intensification of inter-port competition (Hayuth 1981; Starr and Slack 1995). This development was made particularly evident in Europe, where the expanding hinterland coverage changed port industry from one where monopolistic or oligopolistic markets were the norm (with the corresponding 'captive' hinterlands), to one of intense inter-port competition with large 'shared' or 'contestable' hinterlands. Many European container ports now act as gateways to extensive inland networks (Notteboom 2008).

This makes the European port system one particularly interesting for addressing the issue of inter-port competition.

The European container port system is one of the busiest container port systems in the world, encompassing ports that are quite different in terms of size, locational attributes and commodities handled. In Europe, there are about 130 seaports handling containers, of which around 40 are regularly visited by intercontinental container services. In total, in 2010, the European port system handled 4.04 thousand million tons, of which about 900 million tons corresponded to containerized cargo (Notteboom 2013). Figure 1 shows

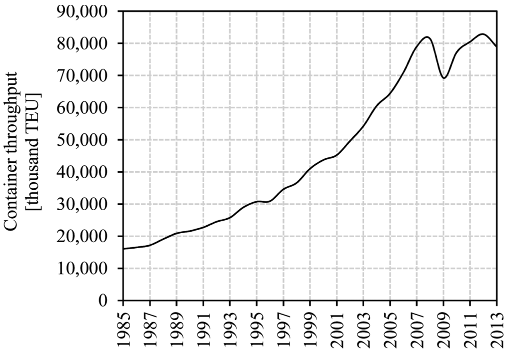

Figure 1. Port throughput in the European port system (1985–2013) [source: data from the respective port authorities].

the container throughput historical evolution for the main ports in the European seaport system (main ports in the Atlantic, UK and Ireland, Baltic, Black Sea, Hamburg-Le Havre, and Mediterranean ranges).

For the analysis of the competition dynamics in the European container port system it is convenient to consider ports as belonging to broader port regions termed port ranges. Given their geographical proximity, ports within each range tend to share some important attributes regarding inter-port competition. For example, the quality of the hinterland accessibility tends to be somewhat similar within each range. This sharing of competitive advantages or disadvantages makes it reasonable to treat ports within each range as belong to the same group in terms of inter-port competition.

This is not to say that inter-port competition within each range isn't as fierce as between port ranges. In fact, considerable research devoted to competition within ranges has been published (see e.g., Klemann 2013, Thorez & Joly 2006 and Loyen et al. 2003). However, inter-port competition within a range also has important consequences regarding competition between ranges. As an example, the ports of Antwerp and Rotterdam are located at approximately 275 km from each other, meaning that there is considerable hinterland overlapping. Fierce competition between these two ports has forced them to develop highly efficient hinterland accessibility and to promote high service quality standards. This reflects itself on lower logistic costs for shippers making use of both these ports in comparison with less efficient ports located elsewhere, such as the Mediterranean ports. This may lead shippers to choose ports located in Northern range, even if their cargo's final destination is located in the natural hinterland of other port ranges.

The European port system can be split in the following port ranges: the Hamburg-Le Havre range, the Mediterranean range, the UK range, the Atlantic range, the Baltic, and the Black Sea. Figure 2 shows the market share of each European port range for 2007.

The Hamburg-Le Havre port range handles about half of the total European container throughput and is one of the main port ranges in the world. Within a distance of about 850 kilometers, 6 major ports are located which together handled about 40 million TEU in 2013 (see Table 1). Three ports in this range count themselves among the top 20 container ports in the world in terms of throughput. Rotterdam, having ranked tenth in 2013, Hamburg (which ranked fourteenth in the same year) and Antwerp (having ranked fifteenth in 2013) are the most significant non-Asian

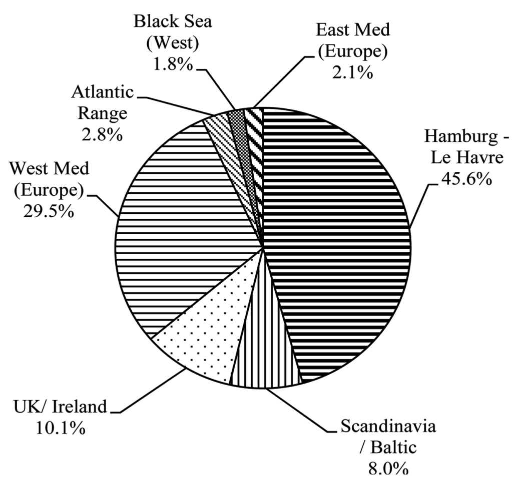

Figure 2. Market share of the European port ranges in 2007 [source: ESPO].

Table 1. Container throughout in the Hamburg-Le Havre port range and the respective market share within the range for 2013 [source: data from the respective port authorities].

Port	Container throughput [thousand TEU]	Share in HLH range [%]
Rotterdam	11,621	28.9%
Hamburg	9,257	23.0%
Antwerp	8,578	21.3%
Bremen/Bremerhaven	5,831	14.5%
Le Havre	2,486	6.2%
Zeebrugge	2,026	5.0%
Total	39,799	100.0%

container ports in the world, ahead of port of Los Angeles (the most significant non-Asian and non-European container port in the world), which ranked 16th in 2013, with a container throughput of about 8 million TEU (Containerization International 2014).

As for the Mediterranean range, it comprises 8 major ports spread over a much wider region, being distributed over a distance of about 3500 kilometers (considering only the western Mediterranean ports, given the relatively insignificancy of eastern Mediterranean ports as shown in Fig. 2). Table 2 lists the 8 most significant ports in the Mediterranean range, including container throughput and respective market share.

While the most significant ports in the Northern range raked among the top 20 container ports in the world, Valencia and Algeciras, the most significant container ports in the Mediterranean range ranked 28th and 34th, respectively, in 2012, with Marsaxlokk and Gioia Tauro lagging far behind, having ranked 56th and 59th, respectively (Containerization International 2014).

A striking difference between the Northern range and the Mediterranean ranges is the existence in the latter of almost pure transshipment hubs, such as Algeciras (Spain), Gioia Tauro (Italy) or Marsaxlokk (Malta) with an average transshipment incidence (i.e., the share of transshipment in total throughput) of over 90%. In contrast, Northern range ports present a much lower transshipment incidence. In this regard, Bremerhaven is the most significant port in the Northern range, with a transshipment incidence of about 51%. Hamburg, the second most significant port concerning transshipment in the Northern range, shows a transshipment incidence of only 34%. Moreover, transshipped containers are double counted. In this way, even a port having between 50% and 66.5% of its traffic comprising transshipments, it is still hinterland traffic which is the most important source of containers. In light of this, no pure transshipment hub can be identified in the Northern range, in contrast with the Mediterranean.

Figure 3 shows the historical evolution of the Hamburg-Le Havre and the Mediterranean ranges market share. The market share of the Mediterranean ports grew significantly between the late 1980s and the late 1990s at the expense of the ports in the Hamburg-Le Havre range. The significant improvement of the market share of the Med is mainly the result of the insertion of transshipment hubs in the region since the mid-1990s. In the new millennium, the position of the northern range has gradually improved while the Med ports lost market share.

Any explanation for the dominance of the Hamburg-Le Havre range port and their almost complete control of the richest market regions of Europe must almost inevitably include the deep regionalization process observed for these ports over a long period of time. The term 'regionalization' is used here in the same sense as in Notteboom & Rodrigue (2005), to mean the development of hinterland accessibility, with the port acting as a starting point for the growth of such logistic network and associated facilities.

The referred dominance makes it very difficult for ports in the southern regions to compete for the richest European hinterlands. In order to counterbalance the dominance of the northern range ports, ports in the Mediterranean range have pursued a strategy of developing transshipment container hubs. Although effective in the initial stages (with the benefits being noticeable for approximately a

Table 2. Container throughout in the Mediterranean range and the respective market share of each port within the range for 2013 [source: data from the respective port authorities].

Port	Container throughput [thousand TEU]	Share in med range [%]
Algeciras	4,343	19.1%
Valencia	4,328	19.1%
Gioia Tauro	3,100	13.7%
Marsaxlokk	2,750	12.1%
Genoa	1,988	8.8%
Barcelona	1,720	7.6%
La Spezia	1,300	5.7%
Marseille	1,099	4.8%
Total	22,694	100.0%

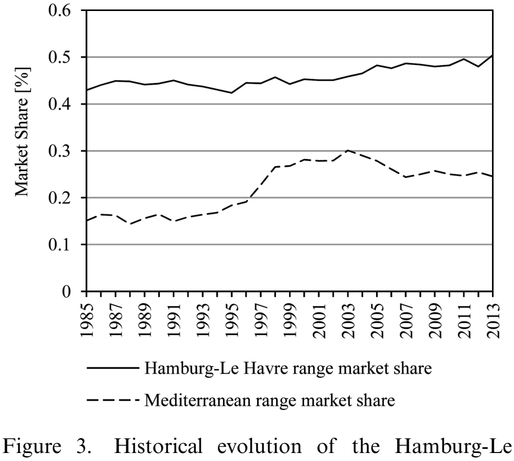

Figure 3. Historical evolution of the Hamburg-Le Havre and Mediterranean ranges market share within the European container ports system (1985–2013). [source: data from the respective port authorities].

decade), this strategy proves to be relatively short-lived for reasons that will be explained in more detail later in this paper but which can be summarized in the following manner: the development of transshipment hubs by-passes the regionalization phase of port development (Gouvernal et al. 2012). Hinterland traffic remains the backbone of port activity while transshipment is a highly volatile business (Ducruet & Notteboom 2012).

In the next section, the causal relationships underlying the historical evolution of container throughput in the considered port ranges are outlined. The causal relationships which will be identified mainly on the basis of published literature devoted to competition between the Hamburg-Le Havre and the Mediterranean range, will then be translated to a simulation model, which will serve as a validation tool for the currently proposed explanation for the observed dynamics and, at the same time, to pinpoint the advantages and downturns of the strategies pursued within each port range.

2 CAUSAL RELATIONSHIPS IN PORT RANGE COMPETITION

In this section, the causal relationships explaining the dominance of the Hamburg-Le Havre range that have been put forward in published literature are depicted by means of Causal Loop Diagrams (CLDs).

CLDs are an appropriate manner of illustrating causal relationships between variables where feedback is present. In CLDs, causal relationships are represented by arrows pointing from the independent to the dependent variable. A plus or minus sign is appended next to the arrow to indicate the nature of the relationship, so that if the value of the dependent value increases (decreases) when the value of the independent value increases, a plus (minus) sign is added. In other words, in a CLD, an arrow points from an independent variable to the dependent one, to denote causality. If the value of the dependent variable increases when the independent variable also increases, then a plus sign is added to the arrow linking the two. Equivalently, when the independent variable decreases, the dependent variable also decreases, in which case, a plus sign is still added to the arrow. Thus, the plus sign means that both the independent and the dependent variables change concomitantly in the same direction, whether it be an increase or decrease. If, on the contrary, the value of the dependent variable decreases when the independent variable increases, then a minus sign is added to the arrow between the two. An equivalent graphical depiction is used when a decrease in the independent variable causes the dependent variable to increase.

After a problem has been depicted through the use of CLDs, simulation may be introduced by translating such CLDs to a system dynamics model.

A system dynamics model can be written as a set of ordinary differential equations:

$$\frac{dx(t)}{dt} = \dot{x}(t) = f(x(t), u(t)) \tag{1}$$

where $\dot{x}$ is the vector of first time derivatives (rates), t is time, x and u are column vectors of the n state variables (levels), and p exogenous variables, respectively.

2.1 *Gateway throughput, regional GDP and logistic performance*

The relationship between trade and economic growth has been addressed by a number of authors. Blonigen & Wilson (2013) have a review of the determinants of maritime trade and its relation with economic growth. The higher the economic output of a region, the more goods are available for trade. In turn, the higher the trade, the greater the economic growth of a region. The strong correlation between GDP and trade is illustrated in Figure 4.

On the other hand, competition between ports is not made between individual ports but rather between alternate inter-modal chains. With inland logistics costs comprising between 40–80% of total container shipping costs, hinterland accessibility plays a decisive role in port competitiveness (Notteboom 2004; Zhang 2008).

A port with a high logistic performance will attract more cargo for a distant hinterland than another port located nearer the shipper but with a much lower logistic performance, i.e., with a higher generalized logistic cost.

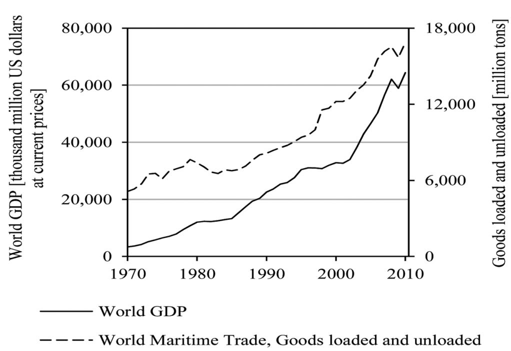

Figure 4. Historical evolution of World GDP and maritime trade (1970–2010) [source: UNCTAD 2014].

As an example of this, an important share of containers originating from Italy do not sail from Italian ports, but rather from ports in the Northern range. A commonly vented explanation for this is the higher efficiency and less costly intermodal organization that links Italy to the Northern range than that linking origin/destination points within Italy itself to Italian ports (Cazzanigga & Foschi 2002).

An aspect worth mentioning in the context of hinterland accessibility in Europe is that of inland waterways. Northern Europe is favored with an extensive network of inland waterways, which is practically non-existent in Southern Europe. Barge transport represents the least costly, albeit much slower, form of transportation.

Given, on one hand, the causality between logistic performance and trade, and on the other the previously mentioned relationship between GDP and trade, a high correlation is expected to exist between logistic performance and GDP (the causal mechanism for this is addressed below). Indeed, Figure 5 illustrates this fact. Countries with a higher GDP per capita (GDP per capita instead of GDP per se in order to take into account each country's dimension) consistently show a higher logistic performance. Logistic performance is quantified here through the use of the *Logistic Performance Index*, *LPI*, an indicator regularly made public by the World Bank, providing both qualitative and quantitative assessments of a country's logistics environment, including performance time and cost data.

Figure 6 is a CLD illustrating the relationship between port gateway throughput, gross domestic product and logistic performance. The shown CLD can be read in the following manner: the higher the

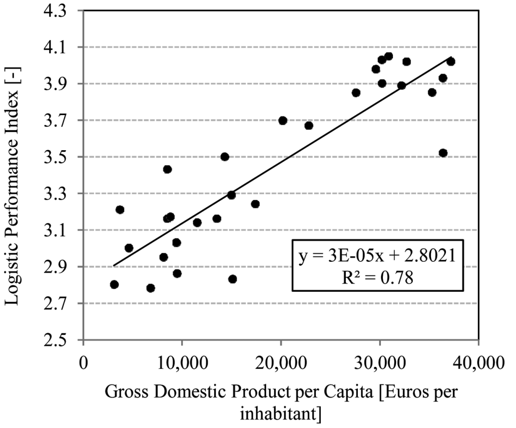

Figure 5. Relationship between logistic performance and GDP per capita [source: World Bank 2014].

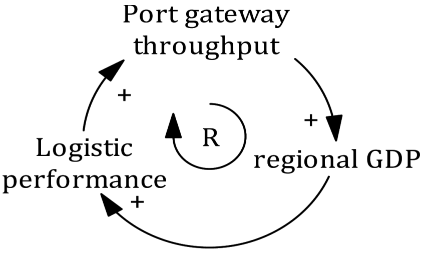

Figure 6. Causal relationships between gateway throughput, GDP and logistic performance.

port gateway throughput, the higher the GDP; in turn, the higher the GDP, the higher the logistic performance (as more resources become available for investment in trade facilitating infrastructures); and finally, the higher the logistic performance, the higher the port gateway throughput (as more users are attracted by the improvement in logistic performance).

Given that the relationships represented in Figure 6 are all mutually reinforcing, a positive feedback loop (also termed reinforcing loop, and hence the 'R' represented in the center of the loop) is said to exist between the represented variables.

It should be noticed that Figure 6 pertains only to gateway traffic, in this way excluding transshipment activity. The reason for this is the following: transshipment traffic is not directly related to economic development in the region where the transshipment port is located, but rather, to economic growth in the regions where the transshipped goods are produced or imported to. This does not mean however, that the transshipment activity does not contribute to economic development of the region where the port is located. However, this contribution is somewhat marginal and related to port cargo services (i.e., stevedores, port authority, etc.). In other words, the economic spin-offs of transshipment are somewhat limited.

2.2 *The insertion of transshipment hubs in the Mediterranean*

Before the 1990s, the Mediterranean ports were largely by-passed by maritime traffic in the Asia-Europe trade. However, over the last 20 years, the increasing volume of containers making use of the European ports on the one hand, and the time savings for large vessels on oceanic routes that pass through the Mediterranean as compared to travel times to reach the Northern range ports on the other, has favored the insertion and growth of transshipment hubs in the Mediterranean (Cazzanigga & Foschi 2002). This is the reason for the noticeable increase in market share

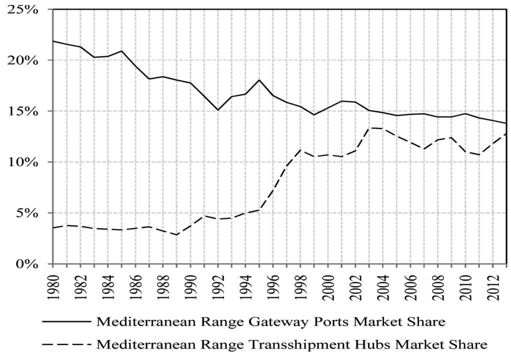

Figure 7. Historical evolution of gateway and transshipment container throughput in the Mediterranean in terms of market share within the European container ports system (1980–2013). [source: data from the respective port authorities].

for Mediterranean range ports at the expense of Northern range ports seen in the mid-1990s. Nonetheless, transshipment is a highly footloose and competitive business. Figure 7 shows the evolution of Mediterranean gateway ports and transshipment hubs market share from 1980 to 2013.

After a continued growth starting at a 3,5% market share in 1980, Mediterranean hubs competitive position peaked at an approximate 13.3% in 2003. However, in the last few years, a small decline was observed for Mediterranean hubs as volume growth in mainland ports allowed shipping lines to shift to direct calls (Notteboom 2009).

3 SYSTEMS ARCHETYPES FOR PORT COMPETITION

Systems archetypes are commonly occurring structures (i.e., relationships between variables) that exhibit typical patterns of behavior over time. Systems archetypes may help to explain a given system's observed behavior but also to identify possible solutions to a given dynamic problem (i.e., an unwanted observed behavior over time). They have been used recently for modelling container terminal management policies (Santos et al. 2014).

In this section, a set of systems archetypes is used to explain the dynamics observed in port competition between the Hamburg-Le Havre and the Mediterranean ranges.

3.1 *'Success to the successful' in port range competition*

Port users choose ports on the basis of the incurred costs and the logistic performance of the logistic chain associated with that port (Meersman et al. 2010). If a port is already part of a logistic chain offering the best solution in terms of generalized costs, it is likely that that port will be selected. This will further aggravate the gap between the chosen port and its competitors as more resources (i.e., income) are available for capacity expansion and further increase in logistic performance (e.g., investment in trade facilitating infrastructures), thereby increasing the likelihood of that port being chosen again in the future.

This situation corresponds to a 'success to the successful' archetype.

In a 'success to the successful' situation, two or more parties (e.g., two port ranges) compete with each other for a limited pool of resources (i.e., container traffic) to achieve success (market dominance in the European container port system). If one of them starts to become more successful (or if historically already more successful), it tends to garner more resources, in this way further increasing its success in relation to the other parties. Its initial success justifies channeling more resources to it while depriving the other competitors of resources and opportunities to build their own success.

The Northern range ports have developed an effective inland transport network (road, rail and barge), satellite terminals, inland ports and logistic zones to such a degree that they now control most of the richest market regions of Europe. Their dominance makes it very difficult for ports in other regions, namely in the southern and eastern fringes of the continent, to compete with them (Gouvernal et al. 2012).

Figure 8 shows the CLD for the 'success to the successful' archetype for the competition between the Hamburg-Le Havre and the Mediterranean port ranges. The depicted CLD can be read in the fol-

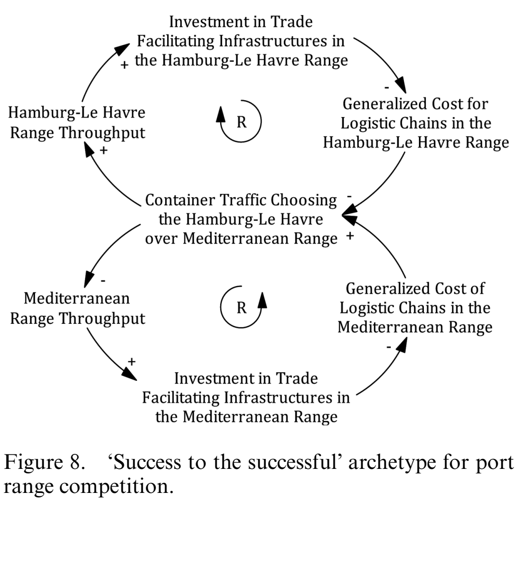

Figure 8. 'Success to the successful' archetype for port range competition.

lowing manner: the higher the Hamburg-Le Havre range throughput, the more resources are available to invest in trade facilitating infrastructure (e.g., road, rail, inland terminals). In turn, the higher the investment in trade facilitating infrastructure the lower the generalized cost for logistic chains associated with ports in the Hamburg-Le Havre range, and the lower the logistic cost, the more container traffic choosing ports in the Hamburg-Le Havre range as part of their logistic chain. Finally, the more the more container traffic choosing ports in the Hamburg-Le Havre range as part of their logistic chain the higher the Hamburg-Le Havre range ports throughput, in this way closing the reinforcing loop pertaining to the Hamburg-Le Havre range.

The same reasoning is applied in reading the dynamics associated with the Mediterranean range. The higher the logistic cost associated with ports in this region, the more the container traffic choosing ports in the competing range (i.e., the Hamburg-Le Havre range) as part of their logistic chain.

The presence of the two reinforcing feedback loops leads to an ever increasing gap between each of the port ranges' market share.

The fact that the Northern range ports are in an advantaged position (which, if no other dynamics are present, will tend to increase with the course of time as explained above) is illustrated by Figure 9, depicting the average road network density in each of the port ranges. In fact, the average value for the *Logistic Performance Index* has an average value of approximately 4 for the regions in the Hamburg-Le Havre range hinterland, while the same indicator has an average value of approximately 3.5 for the Mediterranean range hinterland.

3.2 *The 'limits to growth' for transshipment hubs*

As mentioned earlier, transshipment activity, although initially presenting a possibly considerable growth rate, eventually meets a limit to its growth as the increase in cargo destined to a given gateway port justifies a change from a hub-and-spoke network configuration to one of direct calls on the part of the shipping lines. This situation corresponds to the 'limits to growth' archetype.

In a 'limits to growth' situation, some measures lead to an initial growth (the insertion of transshipment hubs in a region), which favors even more of these actions to be taken (i.e., further investment in new regional hubs or in expanding the capacity of the existing ones). Over time, however, the success itself (i.e., the growth of transshipment activity) causes the system to encounter limits, eventually halting further growth (i.e., as the growth in traffic destined to a given gateway port justifies a shift to a direct call scheme).

Figure 10 shows the CLD for the 'limits to growth' archetype for transshipment hubs.

It should be noted that, in the model presented in this paper, the limits to growth archetype for transshipment ports is considered only for the Mediterranean range as it is only in this region that pure transshipment hubs can be found. In this paper, port throughput for the Hamburg-Le Havre range is considered to include both gateway and transshipment cargo, given that no pure transshipment hub is identifiable in this range.

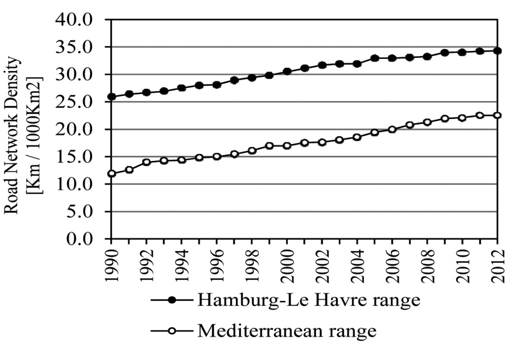

Figure 9. Road network density in the Hamburg-Le Havre and Mediterranean ranges hinterland [source: Eurostat 2014].

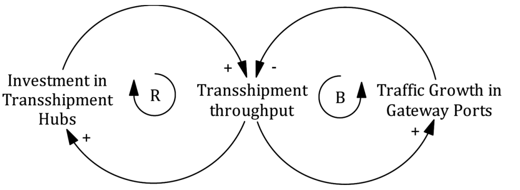

Figure 10. The 'limits to growth' CLD for transshipment hubs.

4 SIMULATION MODEL

For the translation of a causal diagram to a set of n first order differential equations, a set of state variables that describe the system must be chosen. However, many different sets of state-variables can be chosen to describe any given system. A common choice is those variables that are measured to assess the system's performance (sometimes referred to as key performance indicators). In the context of regional inter-port competition, in principle, these would include the total throughput for each range.

Once the appropriate set of state-variables has been identified, the state-space description of the system through a set of first-order differential equations is fairly straightforward. In particular, the translation of systems archetypes to sets of coupled differential equations has been addressed by Bourget-Diaz & Perez-Salazar (2003). The referred authors propose the following mathematical structure for the 'limits to growth' archetype:

$$\dot{x}(t) = Kx(t)\left(\frac{L - x(t)}{L}\right) \quad (2)$$

where the term in brackets is the fractional difference between the limit to growth L and the current system state $x(t)$. The variable limit to growth, L, is obtained by calibrating the model so that its behavior mimics historical data, including the timing of inflection point.

When applying this archetype for transshipment hubs in the Mediterranean x(t) refers to the transshipment throughput and K is a coefficient for fitting port throughput to historical data.

Model calibration for determining an appropriate value of K involves a determination of what are termed statistically as maximum likelihood estimates. In Vensim™ (the system dynamics software used for this research) this is achieved by maximising a payoff function. Initially this function has a negative value and the calibration optimisation process should ensure this becomes less negative. An ideal payoff value, after optimisation, would be zero. During the calibration search, the difference between the model variable and the data value is taken, multiplied by a weight, squared and added to the error sum. This error sum is minimised.

The equations for the 'success to the successful' are the following:

$$\dot{x}_1(t) = K_1 x_1(t)(x_1(t)/(x_1(t) + x_2(t))) \quad (3)$$

$$\dot{x}_2(t) = K_2 x_2(t)(x_2(t)/(x_1(t) + x_2(t))) \quad (4)$$

where $x_1(t)$ is the Hamburg-Le Havre range container throughput, $x_2(t)$ is the Mediterranean range gateway container throughput, and K_1 and K_2 are coefficients for adjusting each port ranges growth rate to historical data. The terms between brackets represent each port range market share, so that the port range with the highest market share will tend to further strengthen its position over time.

The system dynamics model should serve to translate the qualitative description found in the literature into a quantitative one. Moreover, it should serve to better understand the causal relationships affecting port range competition. It should be noted however, that, while system dynamics models are particularly apt for understanding behavioral tendencies (i.e., growth, stagnation, oscillation), they are not well suited for forecasting purposes or "point prediction". Forecasting would imply a complete knowledge and control of all the variables affecting the system's behavior.

5 RESULTS

Figures 11–13 show the model results for container throughput between 1980 and 2012, while Table 3 shows the model errors. Model results, in particular the market share evolution over time suggest the aptitude of the proposed archetypes to explain the observed dynamics in port competition between the Hamburg-Le Havre and the Mediterranean range.

Model errors shown in Table 3 are assessed in terms of two measures of fit: the Mean Square Error (MSE) and the Root Mean Square Percentual Error (RMSPE). Both these measures are suggested by Sterman (1984) as appropriate formal measures of goodness-of-fit for system dynamics models.

The MSE is calculated as in equation 5:

$$MSE = \frac{1}{n}\sum_{t=1}^{n}(S_t - H_t)^2 \quad (5)$$

Where n is the number of observations, S_t is the simulated value at time t, and H_t is the observed

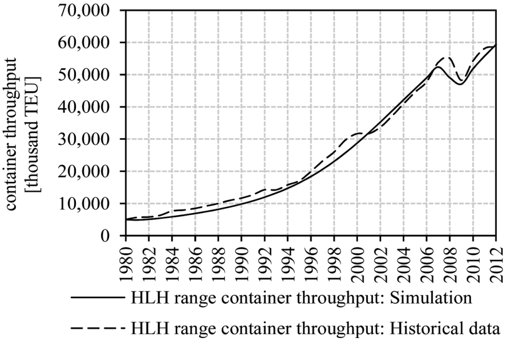

Figure 11. Hamburg-Le Havre range container throughput (1980–2012): historical data and model results.

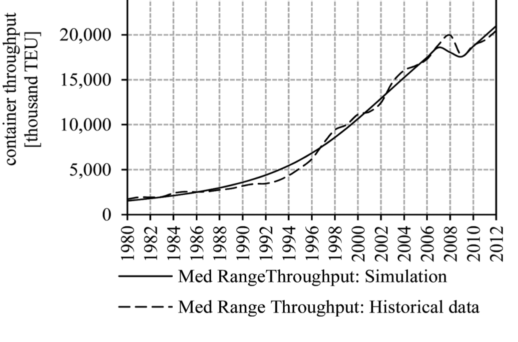

Figure 12. Mediterranean range container throughput (1980–2012): historical data and model results.

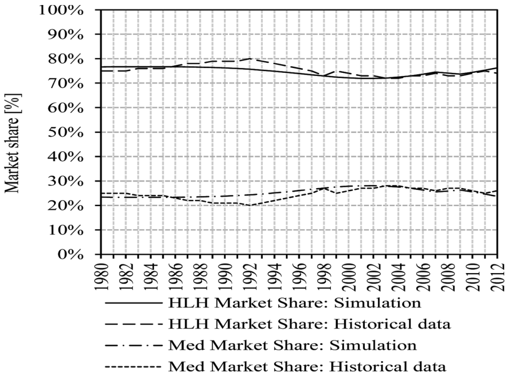

Figure 13. Hamburg-Le Havre and Mediterranean port ranges market share evolution within the European container ports system (1980–2012): historical data and model results.

Table 3. Model errors.

Variable	MSE	RMSPE [%]
HLH range throughput	4,181,441	0.1%
Med range throughput	438,507	0.1%
HLH market share	0	0.0%
Med market share	0	0.1%

value (historical data) at time t. The MSE has the advantage that large errors are weighted more heavily than small ones. Additionally, errors of opposite sign do not cancel each other.

The RMSPE, a normalized measure (and as such more easily interpreted than MSE), is defined as:

$$RMSPE = \sqrt{\frac{1}{n}\sum_{t=1}^{n}\left(\frac{S_t - H_t}{H_t}\right)^2} \quad (6)$$

6 CONCLUSIONS

The aptitude of the selected systems archetypes for depicting the competition between the Hamburg-Le Havre and the Mediterranean port range allows two main conclusions to be drawn, one concerning the role of transshipment hubs in port range competition and the other concerning the possibility of historically least favored range in becoming more competitive da re-gaining market share.

As the qualitative description of published literature suggests, which is supported in a quantitative manner in this paper, a strategy based on the insertion of transshipment hubs in order to gain market share proves to be of limited value both in magnitude and in time. This derives from the fact that no direct causal relationship is observed between relevant regional economic development and the insertion of transshipment hubs, as transshipment cargo pertains to firms located in other ports hinterland. Moreover, as transshipment activity unfolds, it imposes a limit on itself since the growth in volume enables the attaining of economies of scale on the part of shippers justifying a shift to a direct call scheme.

As for the possibility of the Mediterranean range regaining market share in a consistent and more permanent manner, both the model's structure and reviewed literature suggest that this must achieved with an emphasis on gateway traffic. However, as time goes by, the resources needed to counterbalance the advantage gained by the Northern range ports in terms of logistic performance through a long standing process of port regionalization tend to increase even further, which may help explain the preference for the immediate solution (the insertion of transshipment hubs) instead of a more fundamental one (the development of an efficient transport network in the hinterland with the Mediterranean ports acting as starting points for such growth).

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Inland navigation

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Technical feasibility study of iron ore export using Douro river

D.B.V. Lima, T.A. Santos & C. Guedes Soares
Centre for Marine Technology and Engineering (CENTEC), Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal

ABSTRACT: One technical solution for the export of iron ore from Moncorvo mines, near the Douro River, in Northern Portugal, has been analysed relying on the fluvial transportation using Douro River and maritime transportation to the port of Aveiro. The technical feasibility of the fluvial-maritime transport mode has been studied, first through the dimensioning of the fleet necessary for the transport of 8 million tons of iron ore per year using basic queuing theory principles. Douro river transport fleet and dry bulk terminal dimensioning have been carried out separately. Then a coupled simulation model including the dry bulk terminals and Douro river transport fleet has been developed to verify the initial dimensioning taking advantage of variables manipulation, animation of entities and stochastic input parameters for the operation and arrival times. Fleet and terminal dimensioning is then updated and conclusions of the study are drawn regarding the technical feasibility of using river Douro to export the required volume of iron ore.

1 INTRODUCTION

Portugal possesses an iron ore field in Torre de Moncorvo evaluated at 120 million tons, according to Dinis da Gama (2012). This iron ore is located in a mountainous region 175 km from the coast, as shown in Figure 1.

A mine was explored in the past in this location, but it was closed in 1986. The iron content of the ores in Moncorvo is relatively low (40–50%) and there is also a significant content of phosphorus (~0.5%) which needs to be removed using difficult and expensive industrial processes. Under these conditions, the economic viability of the exploration of this mine is only attained with high prices for ore in the international markets.

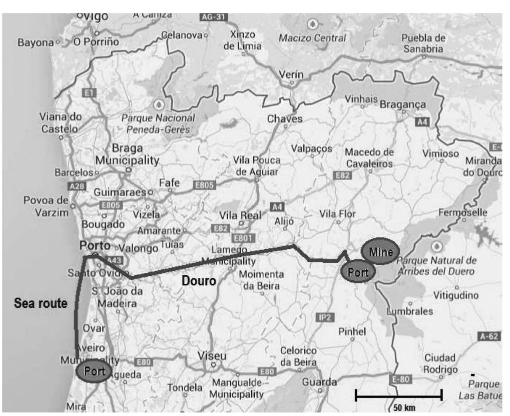

Figure 1. Douro river and location of mine.

The increase in price for iron ore in recent years has now made possible considering the exploration of this mine again. For that purpose, two main issues remain to be solved: the high content in phosphorus of the iron ore in Moncorvo and the transport of the ore to the coast. This paper will deal with the later problem.

Different alternatives exist for the transport of the iron ore to the coast: river, slurry pipeline, rail or road. Once in the coast, two different ports could be used for the transhipment of the ore to seagoing bulk carriers: Aveiro or Leixões.

The main objective of this work is to evaluate the technical feasibility of using river Douro to transport the iron ore to the coast. For that purpose, the fleet necessary for carrying 8 million tons of ore per year to the coast is evaluated. It should be considered that this is an absolute maximum value of yearly production, to be reached after some years of operation of the mine and if forecasts for ore stock are correct. Smaller values of yearly production can in fact be found in different sources. However, the highest value was assumed in this study in order to test the feasibility of using river Douro, which currently has clear navigational limitations.

This study evaluates also the impact of the distances to be traveled, the minimum travelling times considering the restrictions in the river and its effects in the capacity of the river to allow the flow of such high quantities of cargo. Finally, the size and characteristics of the dry bulk terminals necessary to handle and export the iron ore are also evaluated, in terms of necessary area, quay length, number of berths, yard stacking capacity and cargo handling equipment.

2 INLAND WATERWAYS TRANSPORTATION

2.1 *Douro river*

Douro river is an inland waterway located in northern Portugal, with an extension of 200 km from the mouth to the confluence with Agueda river, in the border with Spain. The river has a difference in height of 125 m which is bridged through 5 dams, used for hydroelectric powerplants and fitted with locks: Crestuma, Carrapatelo, Régua, Valeira and Pocinho. Figure 2 shows two of them.

The depth of the river is currently of 2.5 m between Pinhão and Pocinho and 4.2 m in the other parts of the river. The breadth of the river varies between 40 m and 60 m but the locks in the dams effectively restrict the breadth of ships to 11.4 m. The locks also restrict the length of ships to 86 m. The river is currently used predominantly by passenger ships (river cruise vessels), recreational crafts and some cargo ships.

There are commercial ports in different locations: Sardoura, Várzea do Douro, Régua—Lamego e Vega Terrón. From December to February the maximum flowrate allowing safe navigation (600 m^3/s) is often exceeded, causing the interdiction of the river during around a month.

Furthermore, during winter, navigation at the mouth of the river can also be restricted due to bad weather. Currently, navigation is only possible during the day and there are six locations in the river where the simultaneous traffic in both directions is not possible for ships with length above 20 m. A detailed description of the river particularities can be found in Peixeiro (2012).

2.2 *Ports in northern portugal*

Once the iron ore has reached the mouth of river Douro, there are two possible ports where it can be transshipped to larger ships for export: Leixões and Aveiro. Leixões is located 2.5 miles north of the river Douro and is a large multi-purpose port with a quay lenght of 5 km. It does not have a dedicated dry bulk terminal of the size necessary for handling the large volumes of ore. Maximum depth is currently 12 m allowing for large bulk carriers of the panamax size to be handled. A new dry bulk terminal would have to be built, probably in an area conquered to the sea, requiring a significant investment.

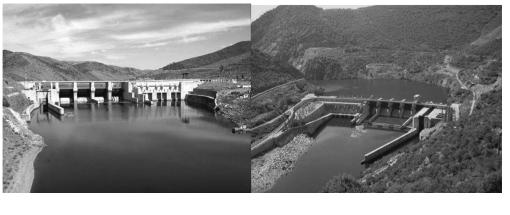

Figure 2. Pocinho and Valeira dams.

Another option would be to convert the existing general cargo and dry bulk terminal to export iron ore. However, this terminal allows at maximum ships of handymax size to be berthed, is located very close to the city, so the environmental impact would certainly be a significant issue. Furthermore, the area which is available to create a large enough yard is limited. For these reasons, the port of Leixões will not be considered in this study, although this option remains under consideration.

The port of Aveiro is located 31 miles south of river Douro. It is well integrated in the road and rail network. It does not have a large dry bulk terminal but the necessary area is available and located suitably far from urbanized areas. Currently, ships with draught up to 10.5 m, length up to 200 m and breadth up to 30 m (handysize bulk carriers) can be handled. Inside the port, a 12 m depth is generally available. With an increase of the depth at the entrance, handymax size vessels with a draught of 12 m could be handled.

The restrictions in both ports imply that, without major investments in increasing the water depths and in creating sufficient area for the yards (in Leixões), bulk carriers larger than handymax size cannot be received. The consequence is that economies of scale cannot be fully used, as is common in many iron ore trades, where capsize vessles are generally used. However, as indicated in UNCTAD (2013), many handysize vessels are employed in the iron ore trade between India and China. Also, due to size restrictions in Japanese ports, ships up to handymax size are also common in trades leading to these ports. Finally, as shown in Barry Rogliano (2014), handymax vessels are also common in the coal trades towards India and China and in the bauxite ore and nickel ore trades from Indonesia to China.

The use of handymax vessels of 50000 dwt implies, in this project, that 160 ships per year are required to carry 8,000,000 tons of iron ore. Therefore, each ship needs to be loaded in a maximum of 2 days, keeping 45 days per year as an allowance for bad weather and faults in equipment.

An interesting project has been in operation in Brasil since 2012, see Oldendorff (2014), where iron ore is exported from Santana in the Amazon river using handymax vessels due to limited water depth. The ore is taken to Trinidad and Tobago (1250 miles away), where it is transshipped offshore (but in sheltered water) by two floating cranes, with total loading rates of 30000 tons/day. This allows a capsize vessel to be loaded in 6 days, implying also that 4 handymax vessels can be unloaded in the same 6 days. During the first 4 months of this project, 2,000,000 tons were transshipped in this manner and taken to China and the Arabian Gulf.

In this context it appears to be possible, from technical and economical points of view, to use handymax vessels between Portuguese ports and European ports to supply steel mills in Europe with iron ore from this much closer source (distance from Aveiro to Rotterdam is 1130 miles). If possible, supramax vessels are to be used due to its superior capacity (up to 60000 dwt), but the available draught should then be clearly above 12 m. This economical study needs to be carried out but it is not within the scope of this paper.

2.3 *Inland waterways used to transport dry bulks*

Inland waterways are used extensively in many countries to transport b44ulk cargoes of different types. Examples are the river and canal network in northern Europe connecting ports such as Rotterdam and Antwerp to the heartland of Europe and the Mississipi river in North America.

The best example of the transport of iron ore using a river is in India, where several iron mines in the region of Goa are connected to the coastal ports (Mormugão and Panjin) through the rivers Zuari and Mandovi, navigable up to 60 km inland. There are more than 30 jetties near the mines and a fleet of some 250 barges with a total capacity of 390000 tons transports the iron ore to the ports, as shown in Figure 3. Annually, 37 million tons of iron ore are transported to the ports, according with a report of Halcrow Group (2007).

Another example of river transport being used for cargo is the bauxite transhipment operation in

Figure 3. Barges used for carrying iron ore to Mormugão.

Guyana, where 2.0–2.5 million tons/year are taken from a mine 131 miles upriver Berbice by a fleet of 20 barges (3500 dwt each). These barges are offloaded to handymax vessels at the river mouth using a floating crane capable of transferring 20000 tons/day.

2.4 *Simulation of traffic in inland waterways*

A significant number of studies have been dedicated, in recent years, to the simulation of integrated transport chains. An example is the study of the port of Seville, including river navigation, lock operation and cargo handling, by Cortés *et al.* (2007). Jagerman and Altiok (2003) apply queuing techniques to terminals handling dry bulks. Campbell *et al.* (2007) carried out research into decision making tools for handling congestion in locks in the Mississipi river. Using simulation approach, Frima (2004), analysed Rio de La Plata capacity to handle increased fleet size in the waterway, a problem which may also exist if dry bulk transport is undertaken at a significant level in river Douro. Other examples of inland navigation simulations include the study by Altiok *et al.* (2012) of the Delaware river using a discrete-event simulation software, Arena, see Altiok and Melamed (2007). This type of software has also been used for modelling the traffic in the Strait of Istanbul and the Panama Canal, as shown in Almaz *et al.* (2006) and Golkar *et al.* (1998), respectively. Also of importance are recent studies into the integration of Geographic Information Systems (GIS) with simulation models of traffic flow on inland waterways, see Biles *et al.* (2004).

3 DIMENSIONING OF BULK BARGE FLEET

3.1 *Selection of the bulk barge design*

For the dimensioning of the bulk barge fleet it is necessary first to select the standard barge design. If there are locks in the river course, normally the barge dimensions are determined by the lock dimensions. Other important factors are the water depth in the river (if less than existing in locks), river basin composition that could demand greater underkeel clearance, restricted air draught due to bridges, large river course curvatures, just inland or inland-coastal operation, etc.

In the case of Douro river, it is considered as physical limitation for the design of the bulk barge, the lock dimensions, despite the fact that shallower zones exist nowadays. Due to the need for some limited coastal navigation, the inland vessel should have some capability for navigation in coastal waters. Other vessel characteristics, such as the speed, are obtained from available information provided by the Douro River Authority, see Decreto-lei N°344-A/98.

Figure 4 shows examples of two possible solutions for bulk barges, one is actually a small coastal bulker with the dimensions required for river Douro navigation and the other a pushed barge and its tug. However, this later solution is considered not suitable for coastal water navigation to Aveiro or Leixões.

Table 1 shows the inland coastal vessel (called Douromax, following Oscar Mota (2012)) main characteristics, most notably the cargo deadweight of around 2000 tons. Due to river limitation, the characteristics of coastal bulkers should not differ too much from these.

3.2 *Calculation methods used to dimension the fleet*

In a first step, simple formulas are used within an excel spreadsheet to approximately dimension the fleet (equations 1 to 5 and queuing theory equations M/M/1 type).

$$T_{load} = T_{unload} = \frac{Cargo_{DW}}{Loading\_rate} \quad (1)$$

$$T_{nav\_upstream} = T_{nav\_upstream} = \frac{Distance_{km}}{V_{knots} * 1.85} \quad (2)$$

$$\begin{aligned} \text{RVT} = & T_{nav\_upstream} + T_{nav\_downstream} + T_{manoeuvre} \\ & + T_{load} + T_{unloaoad} + T_{loacks} + T_{wait\_locks} \end{aligned} \quad (3)$$

Figure 4. Pushed barge and small coastal bulker.

Table 1. Main characteristics of inland coastal vessel.

Ship data		
Id.	Douromax	
Ship speed	11.2	Knots
Length between perp.	82.5	[m]
Breadth	11.3	[m]
Summer draft	3.7	[m]
CB	–	
LW	–	
DW	2574	[t]
Cargo deadweight	2000	[t]

Table 2. Input parameters of simple model.

Item:		
a. general		
Operat. days	330	[days]
Operat. hours	24	[h/day]
b. ports		
(Un) Loading rate	300	[t/h]
Tmanoeuvre	1	[h]
c. voyage		
Distance	186	[km]
Velocity (V)	11.2	[knots]
d. locks		
Number	4	[–]
Lock time	45	[min]
Arrival rate	0.5	[ship/h]

Table 3. Fleet dimensioning-Aveiro.

Fleet size and main data		
RVT	54.44	[h]
Nb_voyages	145	[voyages]
Fleet	25	[vessels]

$$Nb_{voyages} = \frac{Operat_{days} * Operat_{hour}}{RVT} \quad (4)$$

$$Fleet\_size = \frac{Demand}{Cargo_{DW} * Nb_{voyages}} \quad (5)$$

The input parameters for the equation are listed in Table 2. In section 4, the fleet dimensioning will serve as input for the integrated model and checked against the annual throughput of the model. Note that only 4 locks have to be passed because the inland terminal is to be located just downstream of the Pocinho dam. Operating hours have been taken as 24 h/day.

Performing the necessary calculations, the required fleet size for taking the cargo to the port of Aveiro is as shown in Table 3.

For fleet dimensioning, it was considered that the total travelled distance is 231 km. The Round Voyage Times (RVT) and number of voyages are also shown in the same Table. Peixeiro (2012) carried out an estimate of required fleet size which compares well with these values.

4 DIMENSIONING OF DRY BULK TERMINALS

The dimensioning of dry bulk terminals involves determining the main parameters, as listed below:

– Number of berths and characteristics such as location, length, height above water, required water depth.
– Area and lay-out of stocking park.
– Type, number and capacity of cargo handling equipments.

All these items are determined according to the balance of the operational performance and costs. In a first stage, the terminals configurations were analysed independently assuming barge arrival rates that verify the required transport demand and initial stockpile sizes equals to 10% of annual throughput. Due to space limitations the port of Leixões will not be analysed in the dimensioning of terminals.

4.1 *Pocinho inland iron ore terminal*

Pocinho terminal location (Fig. 5) is chosen to be at the same time near the mine, easing the transportation to the barges and downstream of the Pocinho dam in order to make barge transportation time decrease and as a consequence the fleet required also to decrease. The terminal is also positioned in a wider portion of the river, allowing more manoeuvring space.

The cargo enters the terminal by train following the discharge operations in turning wagon devices. The cargo then follows in conveyor belts to the stacker, which organizes the iron ore in stock piles for future loading. The reclaimer pick cargo from stocks putting it in conveyor belt directed to the shiploader, that loads the inland vessel according to its specific loading plan.

A simulation with Petri Nets is conducted to verify the dimensioning of the terminal. The resulting list of equipment and facilities for the terminal with specifications are shown in Table 4.

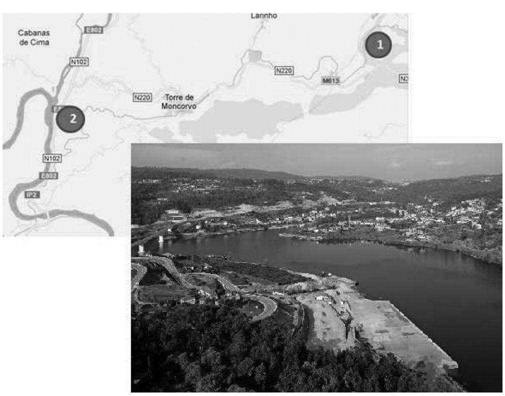

Figure 5. Pocinho terminal location (2), mine location (1) and existing bulk terminal further down the river.

Table 4. Pocinho terminal specifications.

Equipment			
Item	Quantity	Capacity (t/h)	Boom length (m)
Stacker	1	3000	22
Reclaimer	1	2500	38
Shiploader	1	3000	12,5–27
			L × W (m)
Belt conveyor	1	2500	500 × 1.5
Facilities			
Item	Quantity	L (m)	W (m)
Stocking pile	2	500	40
		L (m)	Depth (m)
Quay	2	216	2.5

Figure 6. Aveiro iron ore export terminal location(1).

Table 5. Aveiro terminal specifications.

Equipment and facilities Aveiro terminal			
Item	Quantity	Capacity (t/h)	Ref. length (m)
Unloading			
Grab	2	1250	12,5–27
Berths	2	–	100
Stacker	1	3000	22
Loading			
Reclaimer	1	2500	38
Shiploader	1	3000	12,5–27
Hopper	1		
			LxW (m)
Belt conveyor	2	2500	1500 × 1.5
		L (m)	W (m)
Stocking pile	2	500	40
Berth	1	–	200

4.2 *Aveiro export iron ore terminal*

Aveiro terminal location (Fig. 5) is chosen trying to be in accordance with the port authority zoning, but due to the large amount of cargo, some additional space will need to be incorporated in the bulk terminal. Despite that, the port still has spaces that can be used for further expansion. Figure 6 also shows Aveiro port access channel which was enlarged recently to accommodate handymax vessels.

The operation of Aveiro terminal is in general terms similar to the Pocinho terminal operation but now the terminal must carry out the barges unloading operation and the loading of the seagoing bulkcarriers. For the loading procedure, larger quay length must be available for the operation of handymax vessel.

A simulation with Petri Nets is conducted to verify the dimensioning of the terminal. The list of equipment and facilities for the terminal with specifications are shown in Table 5.

5 SIMULATION OF THE INTEGRATED TRANSPORT CHAIN

Simulation models are very useful to study operation and performance of terminals and various studies have been done using for that purpose discrete simulation based on the Arena software (Silva *et al*. 2006, Silva, and Guedes Soares, 2008). More recently Petri nets have also been shown to be a useful tool for this purpose (Silva *et al*. 2014).

A model integrating the Pocinho dry bulk terminal, Douro river transport and Aveiro Terminal has been developed using Arena software, aiming at verifying the specifications found by previous independent simulations of each system component. The port operation will be simulated using similar blocks developed previously in Petri Nets. The only component that still needs to be defined in terms of simulation blocks is the Douro River downstream and upstream voyages. The simulation also accounts for other vessels that already use the Douro River (modelled according to data obtained from Peixeiro (2012) and checked against river authority information, see IPTM-Delegação Norte e Douro (2013) and climatic effects. In the next sections a brief description of the model operational sets is given. In Figure 7, can be seen the overall sets of blocks implemented in Arena.

5.1 *Description of the douro river transport*

The modelling of Douro River transport is divided in downstream and upstream voyages (Fig. 7, set entitled Integrated Transport System) and in each voyage it is defined travel times between the endpoints (Pocinho and Aveiro Terminals) and between processes that require resources to be available (Restricted Navigation Sector and the locks: Valeira, Régua, Carrapatelo and Crestuma).

Douro and Aveiro access channels are not assumed as requiring pilots due to the size of

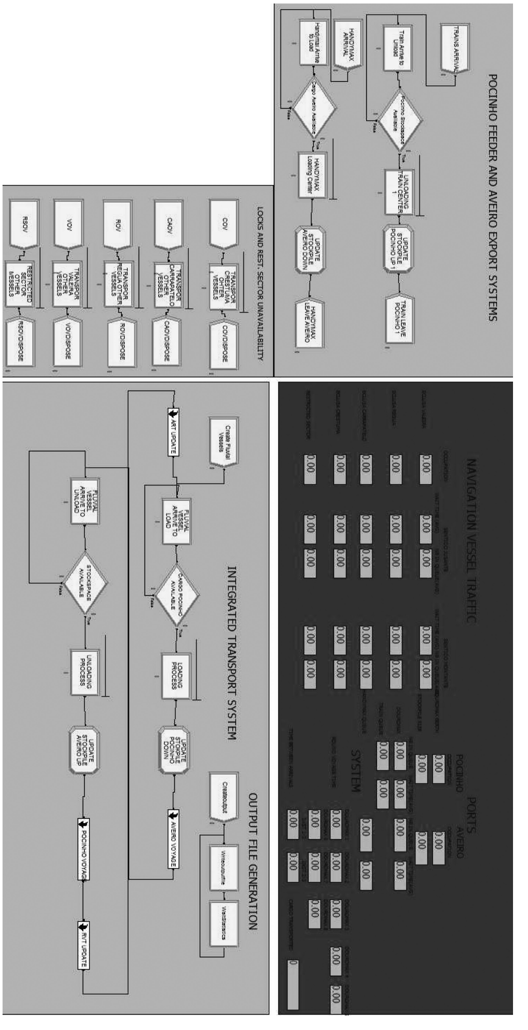

Figure 7. Transport chain model.

inland coastal vessel and being part of Portuguese fleet familiar with the local conditions of navigation. The locks functioning logic modelling is simplified by adding larger uncertainty on the rate of processing incoming vessels.

5.2 *Interaction between the transport system and other process*

Two types of outside processes that affect the transport system are modelled: climatic process and other vessels circulation in Douro River.

The influence of the weather conditions has been modelled indirectly by the configuration of the number of operational days in the simulation parameters dialog. It is considered that navigation is stopped by excessive Douro River flow rate or large ocean sea waves culminating in the closing of Douro and Aveiro access channels.

Other vessels circulation requires locks and restricted sector of navigation, representing concurrent users of the resources (Fig. 6, set entitled Locks and restricted sector unavailability).

5.3 *Results of the simulation model set*

Two modes of results visualization are implemented: Dynamic simulation results viewer (see Fig. 5 Navigation vessel traffic and ports set) and output data file block.

5.3.1 *Dynamic simulation results viewer*

This result mode is used mainly in the debugging of the model. In the dynamic viewer three data subsets are updated as the animation moves forward:

- Navigation Vessel Traffic: shows the occupation rate, waiting queue size and waiting time of each lock and the restricted sector upstream and downstream.
- Pocinho and Aveiro Ports: shows the occupation rate of berths and stock piles (in terms of cargo units) and waiting times together with queue size for barges, Handymax and trains.
- System: shows values of some created variables like round voyage times (in hours) of some Douromax fleet, time between arrivals in Pocinho (in hours) and amount of cargo transported (in tons).

5.3.2 *Output data file block*

During simulation Arena generates internal data and, additionally, the user can define variables and parameters also to be stored. Output data blocks read and store in txt format file internal and user defined data Time steps for the recording are defined and at the present model data read and storage tasks are performed daily.

5.4 *Results of the simulation model*

5.4.1 *Main result*

Barge fleet size increases compared to the initial values calculated on the excel sheet. This is mainly due to the insertion of a restricted sector where only one ship can pass at each time (not considered in the simple model) and simplified queue formulas from queuing theory used in excel sheet (M/M/1 models). Table 6 presents the reviewed fleet size.

5.4.2 *Navigation results*

On what concerns navigation, it is interesting to see the impact of the added barge fleet into the occupation and waiting times on locks and restricted sector. It was verified that the simple insertion of the fleet unsettle the system and measures of improvement on the navigation must be taken. Two measures already proposed in Peixeiro (2012) are taken which are reduction of the transposing time from 45 minutes to 30 minutes and navigability 24 h/day. As a result the occupation levels of the locks achieved stable values (Fig. 8).

Following the occupation rates stabilization, waiting time in queues presents also stable behaviour (Fig. 9). It can be observed higher waiting times in Carrapatelo and Crestuma that achieve the same amount as the transposition operation

Table 6. Fleet dimensions integrated transport chain.

Fleet dimension and main data		
RVT	67.16	[h]
Fleet	34	[vessels]

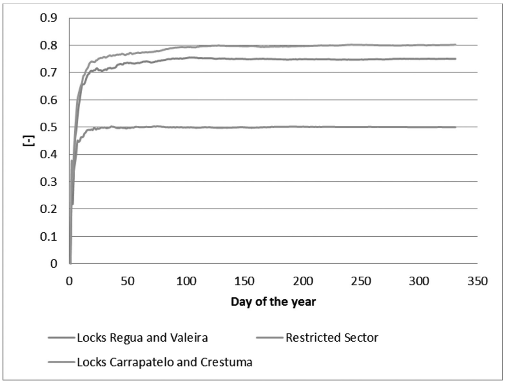

Figure 8. Stabilized values of resources occupation.

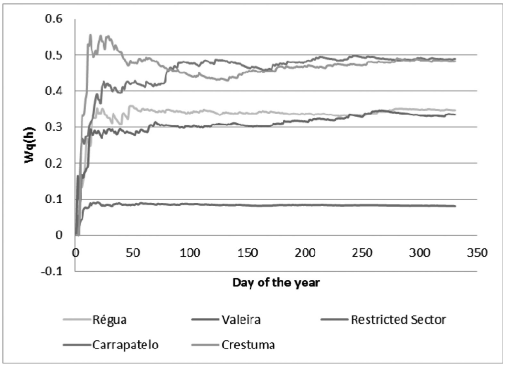

Figure 9. Values of waiting times downstream.

time. In fact, better performance could actually be achieved with the management of congestion in locks that is not modelled in the present simplified system (see Campbell *et al*. 2007).

Due to non-prioritizing of fluxes (upstream or downstream), it was supposed that the waiting times upstream also converge to the same average values. That is what can be seen comparing Figures 9 and 10.

5.4.3 *Port results and other system measures*

The analysis main purpose was to verify the fleet size for the required annual throughput. Besides that stockpile sizes and berths occupations are also analysed. On Figure 11 stockpile sizes where admensionalized by the nominal stockpile capacity (10% of the annual throughput) giving stockpile

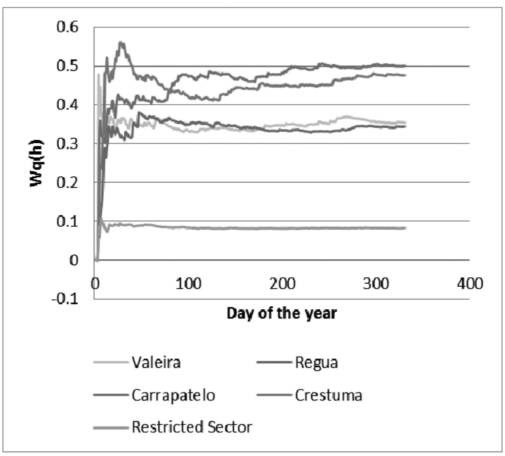

Figure 10. Waiting times upstream.

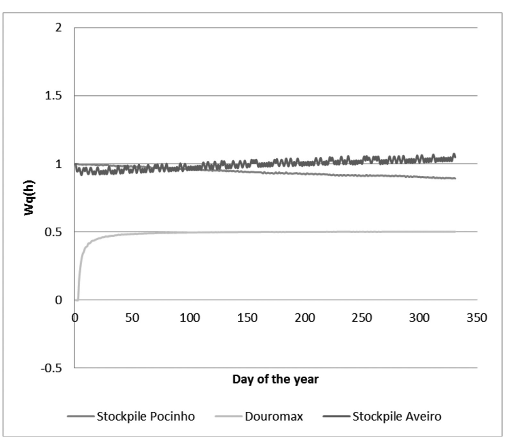

Figure 11. Port results.

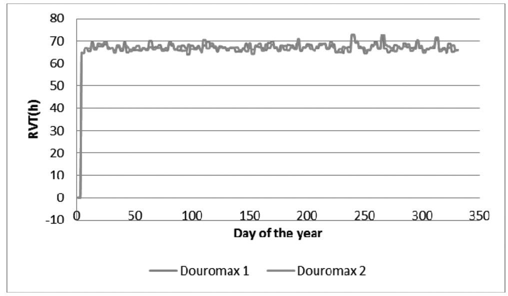

Figure 12. Round voyage times of two barges.

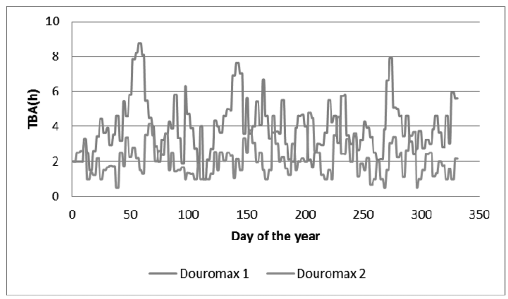

Figure 13. Time between arrivals Douromax 1–2 (blue line) and 2–3 (red line).

occupation rate. It can be seen on Figure 11 a little unsettlement on the stock sizes occupation rate. Despite of that this is even good trends assuming the river off-hire days when Pocinho and Aveiro stockpiles could be balanced again. Berth occupations perform as desirable.

Some interest quantities were also measured for a set of vessels of the barge fleet: round voyage time and time between arrivals for three Douromax vessels are shown on Figures 12 and 13, respectively. Time between arrivals was considered an important measure in order to compare the integrated model against the separated approach since the separate modelling was based on the rate of arrivals and then taking advantage of the infinite queue assumption. It can be seen that arrivals rates varies expressively justifying the need of integrated approach (finite queue theory model).

6 COST ESTIMATE

The scope of this paper is mainly related with the technical feasibility of using river Douro to export the required volume of iron ore, as stated above. However, this section will present some estimates regarding total capital costs of this solution.

It has been assumed that there are three options for transporting the iron ore to Aveiro: rail, slurry pipeline and river. The solution using the river requires investments in the items listed in Table 7. In this table, the cost in the Aveiro terminal infrastructure is the same as in Pocinho, although the terminal in Aveiro needs an additional 220 m of quay length for the handymax vessel, since this berth will always have to exist, irrespective of the solution adopted for carrying the ore to Aveiro. Furthermore, a dry bulk terminal with a quay length of 450 m already exists in the port of Aveiro, which could in fact be used for this purpose, with a number of improvements and adaptations. However, the cost of the Aveiro terminal was included since this existing terminal may already have its own established trade and not be available to conversion.

Table 7 also includes costs stated by the Portuguese government, see Ministério da Economia (2013), for the two improvement projects on the navigation conditions in Douro river. One project (50 million euros) is related to dredging of certain parts of the river to achieve a uniform depth of 4.2 m. Also included in this project are the development of emergency and information systems and the fitting of AIS, VHF and maintenance of buoys. A second project (24 million euros) consist of modernizing the dam's control and monitoring systems, aiming at reducing the operation time.

The overall economic feasibility of using river Douro to transport the Moncorvo iron ore should be accessed by comparing overall transport costs per ton with the other transport modes: rail and slurry pipe. This study has to be done by considering the total costs in the supply chain from the mine to the receiving port, for the three different options of transport mode. Also, both capital costs and operation costs need to be considered. Finally, the external costs (pollution, water consumption, impact in plant and animal life) generated by transport modes need to be considered. These are predominantly multi-disciplinary studies which are out of the scope of this paper.

Table 7. Capital costs (in euros).

Cost item		
Modernization of dams	24,000,000	
Dredging and navigational aids	50,000,000	
Inland coastal vessels	102,000,000	34
Pocinho dry bulk terminal infrastructure	10,000,000	200 m quay/ 15 ha area
Pocinho dry bulk terminal equipment	10,000,000	4 cranes
	5,000,000	Stacker
	5,000,000	Reclaimer
	2,000,000	Belts
Aveiro dry bulk terminal infrastructure	10,000,000	200 m quay/ 15 ha area
Aveiro dry bulk terminal equipment	10,000,000	4 cranes
Total	228,000,000	

7 CONCLUSIONS

This paper has presented a preliminary estimate of the number of river-coastal ships necessary to carry 8 millions of tons of iron ore from Moncorvo to the port of Aveiro. The main characteristics of the dry bulk terminals necessary to load/unload the ships were also estimated.

The main objective of using river Douro is to take advantage of the already existing inland waterway system. The integrated transport solution has been simulated considering the ports, the loading/unloading, the constraints in the river (dams, restricted navigation parts). The fleet size was found to be about 34 river-coastal ships, requiring two berths in Pocinho and in Aveiro (200 m quay length in each terminal). The dry bulk terminal in Aveiro would also include a dedicated handymax size loading berth.

This transport solution is dependent on the implementation of measures on the Douro river to improve navigation conditions: 24 hours navigation and dredging of certain parts of the river to 4.2 m.

Fleet size obtained is considered conservative since lock and restricted areas management strategies are not implemented in the model and these will tend to reduce queuing times. The greater bottlenecks found are the locks operation and the necessity to load the handymax vessels at a high rate in Aveiro. These aspects are however related with the very high quantity of export ore considered in this study.

This work may be improved by considering a smaller annual production of iron ore coupled with improvements in lock control, management of traffic in river and consideration of all restricted navigation sectors. It would also be interesting to simulate the performance of the system in the period of the year immediately after the winter pause or immediately after any pause due to difficult navigation conditions in the river or at the mouth of river Douro (stormy conditions in the sea).

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Analysis of river/sea transportation of ore bulk using simulation process

D. Merino da Silva & M. Ventura
Centre for Marine Technology and Engineering (CENTEC), Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal

ABSTRACT: This work presents a study of the transport of iron-ore by river-sea bulk carrier(s) from a terminal in river Douro to a sea terminal in Aveiro, in the Portuguese west coast. The objective of this study is to make a detailed analysis of this transport problem, in order to obtain the optimum characteristics and specifications of the involved terminals, infrastructures and vessel fleet. The terminals design approach is made by means of simulation. A model was developed, including ships and terminals, which specifies and relates the main parameters that influence the transportation, in order to emulate the real process as close as possible. For the simulations, several scenarios of terminal configurations and cargo equipment were created. All these scenarios were compared by the analysis of performance measures such as annual cargo throughput, port time, waiting times, berth times, rate of equipment utilization in the terminals. Finally some conclusions are drawn from the obtained results about the relative merit of the proposed scenarios.

1 INTRODUCTION

Over the past few years the Portuguese Government has been negotiating the exploration of the iron-ore mines located in Moncorvo. One of the proposals for the transport of the iron-ore, from the mine to an export port, is by means of river-sea bulk carriers using the Douro river inland waterway. This paper proposes a detailed analysis of this transport problem, in order to obtain the optimum characteristics and specifications of the involved terminals, infrastructures and vessel fleet.

Operation research methods, ranging from the classical mathematical formulae of queuing theory to the simulation, are widely used in these types of studies. In (Case & Lave 1971) a model of port operations is developed to determine the optimal capacity of a generic port. Queuing theory is applied to determine the average waiting time for an individual cargo vessel as a function of the arrival rate and service rate distributions (Poisson and exponential respectively). The optimal port capacity is determined cost wise, i.e. comparing the cost of building an additional dock or increasing the service rate with the cost of delaying a vessel. In (Ergin & Yalciner 1991) the optimum port size problem is studied for a container terminal and for a general cargo terminal. The numerical models used in this study assume the ship arrival rate as a Poisson distribution and a service time as an Erlang distribution. The port size is characterized by the quay length and by the number and capacity of the cranes. The optimum port size is then defined as the one with the minimum total annual cost, which is given by the sum of the annual cost of the port (quay and equipment) with the annual cost of waiting time of ships. The same kind of study is carried out in (Dundović & Zenzerovic 2000) for a general cargo seaport. A queuing theory model of the total port costs is developed and the total port cost is obtained by a function of the cost of berths, port cranes, warehousing, labor, ship and cargo.

The optimum port size problem can also be approached by the operational point of view using operational performance indicators to benchmark the port's efficiency and quality of service. In (Wadhwa et al. 1990) a port simulation model is developed as a decision support tool for a bulk coal loading facility. The model concentrates on ships and cargo operations only, it does not concern with warehousing. Several scenarios, with different port configurations (number of berths, cargo handlers and loading rates) are analyzed and a relationship between port capacity, throughput and performance is built. In (Kia et al. 2002) an evaluation of the performance of a container terminal is carried out by testing the relation of the handling technics and their impact on the capacity of the terminal. The simulation model built for this study consists of: ship's arrivals, loading/unloading containers from the vessels, movement of containers within terminal and stacking area and rail/road connections. Two different operational systems are compared according to three performance indicators: berth time, stacking area occupancy and berth occupancy. In (Cortés et al. 2007) a discrete event simulation model is developed to simulate the freight traffic in the Seville port. The simulation model integrates the following main elements: the vessel arrival, lock operation (entrance in the port), dock assignment, container terminal, bulk terminals (cement and cereals), lorry arrival and departure and general cargo docks. The vessel arrival distribution was based on real data from the port. The model produces a variety of port performance indicators as outputs: berth time, waiting time and percentage of storage occupation. In (Ambrosino & Tànfani 2010) is presented a discrete event simulation model developed to help in the expansion plan of a container terminal located in the port of Genoa. The model is made up of three modules: the ship flow, the import and the export container flow. These modules manage the action sequence of model objects (ship, import and export containers) through a series of logistic processes. Real data from the port was collected to be use in the statistical parameters estimation, namely the ship inter-arrival time, the quay crane service time, the truck and train inter-arrival time and the internal transport and yard stacking equipment service times. To analyze the critical factors in the expansion plan of the terminal different scenarios are tested. The analysis is based on several port performance indicators such as: berthing time, container dwell time, import/export throughput, quay utilization rate, etc. In (Sheikholeslami et al. 2013) a discrete event simulation model is developed to study the berth allocation and quay crane assignment in the Rajaee port. The model is divided in three main parts: the berth operation, quay crane operation and tugboat assignment. This model also takes into account the entrance channel traffic and the tidal effects. The influence of different allocation strategies is evaluated and analyzed according to two port performance indicators, the average service time and the average waiting time.

Due to the complexity of the entire transport system presented in this paper (ship, locks, existing waterway traffic, terminals, etc.) the system will be modeled into a discrete event simulation model.

The traditional analytical (mathematical) and queuing methods can be used but they generally do not consider system randomness, and when they do, they required rough assumptions and closed mathematical formulae making the validity of the results questionable (Bichou et al. 2013). Contrarily to queuing formulae, discrete event simulation models are more flexible and versatile; they can be used for the combined random and non-random arrival flow. Also, these types of models can be made complex enough to reflect and emulate the real system behavior.

This transport problem is not recent and has been already studied by some authors. In (Mota 2012) its pointed out the possibility that the iron ore can be transported by a fleet of ships that will represent a new class, the Douromax class. These vessels would have an overall length of 84 meters, a breath of 11 meters, a draft of 3.7 meters, deadweight of 2,900 tons and would be propelled by azimuthal thrusters to increase the maneuverability. The definition of this new class derives from the dimensional limitations impose by the size of the locks. The major bottlenecks existing in the Douro waterway are identified in (Peixeiro 2012) which also proposes some upgrade measures are proposed: dredging to guarantee a depth of 4.2 meters along the entire waterway, implementation of an AIS (Automatic Identification System) to ensure a secure navigation by night (nowadays the navigation is to be made only during daytime) and some improvements in the lock systems. Also in (Peixeiro 2012) is estimated that a transportation of 3.4 million tons of iron ore per year can be made, considering daytime only navigation and 9.6 million tons per year in a 24 hour navigation system. These figures are obtained considering that a Douromax vessel has 2,200 ton cargo deadweight and that a round trip (river terminal to maritime port and back) takes around 48 hours. Peixeiro also refers the need of taking into account the already existing waterway traffic, especially the tourist traffic which is growing every year.

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).

Table 1. Distances between each river section (IPTM, 2013).

Location	Distance from the river terminal Miles
Valeira Lock	17
Régua Lock	38
Carrapatelo Lock	60
Crestuma Lock	83
Sea entrance	95

The river has the minimum width of 40 m in bedrock and of 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

According to (Lodewijks et al. 2007) dry bulk terminals are used worldwide as a buffer between either international or intercontinental transportation and inland or domestic transportation or the other way around. In a terminal there are two main functions or operations: cargo handling (load or unload) and storage. Regarding the direction of the bulk flow a terminal can be classified as an import or export terminal. This factor and the type of bulk handled influence the selection of the equipment resources.

Some considerations about the design and dimensioning of both terminals, involved in this transport route, are presented in this study. The terminals design will be evaluated according to their performance during the several simulation scenarios.

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 characterize 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*

Nowadays there are several types of cargo handling systems available, which can be classified into continuous or discontinuous systems. For the ship unloading there are four basic systems available: grabs, pneumatic systems, vertical conveyors and bucket elevators. The loading of bulk cargo is done, mostly, by means of continuous systems in which a movable ship-loader is fed by a conveyor belt system from the stockpile and drop the cargo on the several cargo holds. Most ship-loaders are provided with a telescopic or spiral chute to reduce drop height and fall speeds into the holds.

In these study the terminals will be assumed to be equipped with ship-unloaders 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. These stockyards are composed by long piles separated by gaps necessary for the conveyor belts and the rails of the stacking and reclaiming systems.

The dimensions of these stockpiles depend of the characteristics of the stacking/reclaiming systems and of the characteristics of the bulk itself. The stockpile characteristics can be obtained by the calculation method in (UNCTAD 1985).

For storage calculations this study assumes that the stockpiles have a constant width of 30 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):

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

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).

Table 2. Typical stockpile dimensions (van Vianen et al. 2011).

	Export terminal	Import terminal
Stockpile lenght [m]	300–1300	300–1200
Stockpile width [m]	30–75	30–85

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 150 m of overall length and 9 m draft.

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.

It is important to note that the terminal in Aveiro is public and some of the available storage areas can be used by other companies. Nevertheless, in this study it is assumed that all the available storage area is available.

4 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.

For a better understanding of its structure the description of the simulation model will be divided in two parts, the operation in the river and the operation in the sea. The description of the process is made following the whole course of the iron-ore starting with its arrival to the river terminal.

4.1 *Ship characteristics*

In this simulation model the ship is represented only by two parameters: the sailing speeds and the cargo capacity (cargo DWT). These two parameters and the other ship characteristics are based on a previous work focused in the determination of the optimum ship characteristics for this case/feasibility study (Merino da Silva & Ventura, 2014).

Table 3. River-sea vessel main characteristics.

LOA	[m]	83.00
Lpp	[m]	80.50
Beam	[m]	11.00
Depth	[m]	4.76
Draught	[m]	3.70
Cargo DWT	[t]	1,775
Service speed (loaded)	[knots]	10.04
Service speed (ballast)	[knots]	10.16

In this previous work two different propulsion systems were tested (MDO and LNG), resulting in two different sets of ship characteristics, specifically different service speeds and cargo DWTs. The characteristics present in Table 3 are the result for the LNG option, which was concluded to be the most viable.

4.2 *River operation*

4.2.1 *Iron-ore arrival*

The transport of the iron-ore from the mine to the river terminal can be done, for instance, by a conveyor belt system or by train, but this aspect is not considered in this study.

In this model the arrival of iron-ore is modeled by a *Poisson* distribution. This kind of distribution is often used to model number of events, such as ship arrivals, during a certain time interval (Gheorghe et al. 2013). It's assumed that the iron-ore arrives already processed in the form of pellets.

4.2.2 *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:

$$T = T_{det} + T_{stoc} \tag{2}$$

where 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).

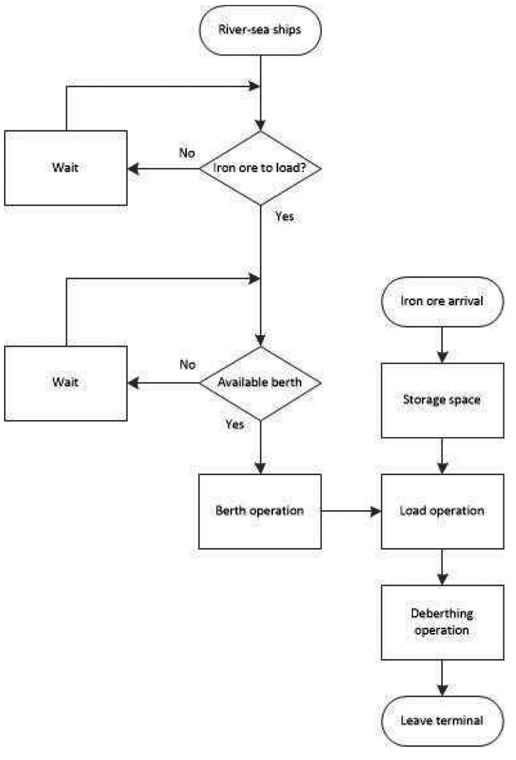

Figure 1. River terminal operation flowchart.

The river terminal operation is represented in Figure 1.

4.2.3 *Berthing and deberthing operation*

The berthing and deberthing operations are also considered in the simulation model. According to (UNCTAD 1985) these operations, together, have a duration of about 2 hours. Since the river-sea vessels are relatively small vessels with good maneuverability, in this model its assumed that these operations will take only 1 hour.

The berth(s) and the 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.

4.2.4 *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). The time spent in each lock operation is represented by a normal distribution with an average of 45 minutes (Mota 2012).

4.2.5 *Existing traffic*

It is vitally important to consider the existing inland traffic because it shares the same waterway and locks. It is therefore necessary to consider in the simulation model the entropy that this traffic will add in the transport system.

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.

4.3 *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.

4.3.1 *Port entrance*

According to the port authorities, every vessel is obliged to have a port pilot during the entrance and berthing operation and 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. Depending on the utilization of these two resources, the vessels may or not have to wait for them at the port entrance.

4.3.2 *Loading/unloading operation*

This terminal will be used by the river-sea bulk carriers witch will unload the iron-ore in this terminal and by handysize bulk carriers that will be loaded concluding the iron-ore circuit considered in this study.

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.

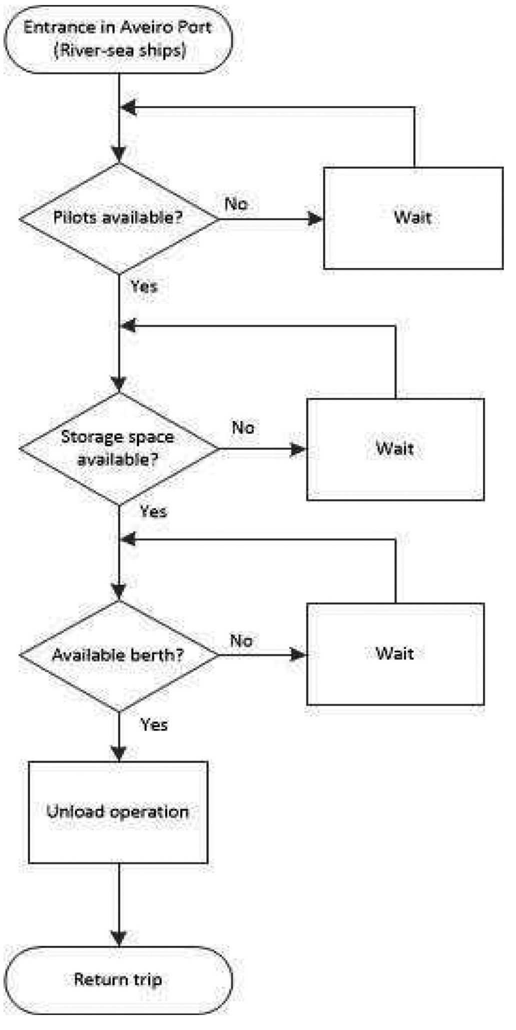

Figure 2. Sea terminal operation flowchart.

The sea terminal operation is represented in Figure 2.

4.3.3 *Handysize vessel*

This class of ship represents the maximum size that can enter in the Aveiro port due to its physical restrictions (see Section 4.3).

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 2003).

The port entrance procedure for this vessel is the same as for the river-sea vessels with the difference that this vessels are obliged to use the tugboat service, hence they may or not have to wait for an available tugboat. It is also 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.

5 SIMULATION

The simulation and the previously described model were developed with discrete event simulation software system.

5.1 *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.

5.2 *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 (see Figure 3). 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).

5.3 *Performance indicators*

The simulation allows the comparison of different scenarios with different port configurations (nº of berths, nº of cargo handlers, handler capacity, etc.). These 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.

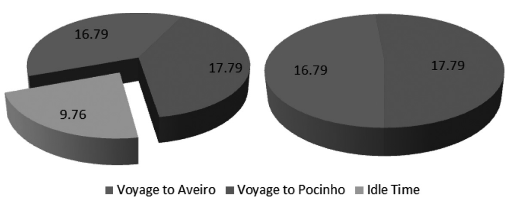

Figure 3. Voyage and idle time, in hours, with schedule restriction (left). Voyage time in hours (right).

5.4 *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). 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.

From scenario to scenario the variable parameters are the number of ships in the river-sea fleet and the terminal configurations, specified by the number of berths and the cargo handler's.

Scenarios 2 and 3 represent a variation in the configuration of Aveiro sea terminal (nº of berths and handler capacity). Scenarios 4 and 5 follow the same line of variation but regarding the Pocinho river terminal. Scenario 6 implements a different configuration in both terminals, with two berths but only one handler for both of them.

All the scenarios are summarized in Table 4.

5.5 *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. For this scenario the PPI port time is 3.75 hours for the river terminal and 6.24 hours for the sea 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

Table 4. 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

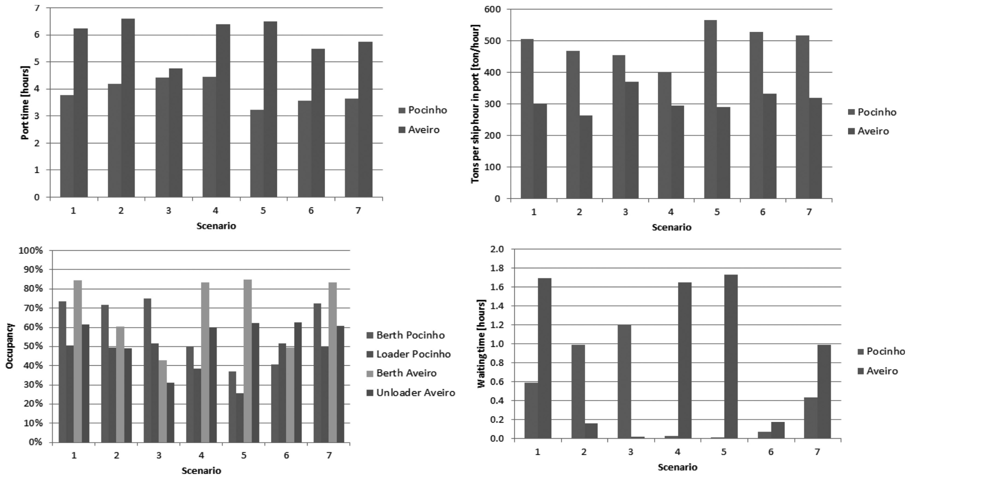

Figure 4. From top to left—Port time; Tons per ship hour in port; Berth occupancy; Average waiting time for berth.

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.

5.5.1 *Berth occupancy factor*

In Table 5 are presented some recommend values for the berth occupancy factor (Memos 2000, UNCTAD 1976). Higher berth occupancy would indicate congestion.

For scenario 1 the berth occupancy in the river terminal it's above these recommended values, 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.

Table 5. Recommended occupancy factors.

Number of berths	Occupancy factor [%]
1	40–50
2	50–60
3	53–65
4	56–65
5	60–70

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.

5.5.2 *Storage occupancy*

The storage occupancy for the river terminal was obtained assuming that the terminal has a storage area of 115,000 m^2 and the sea terminal 151,000 m^2 (see Sections 3.2 and 3.3).

The storage occupancy in the river terminal is very low (see Table 6) 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.

5.5.3 *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 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 0 but the normal with a different normal distribution (Stopford 2003).

5.5.4 *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.

Table 6. Percentage of storage occupancy.

	River terminal		Sea terminal	
Scenarios	Average	Maximum	Average	Maximum
1	24.47	48.05	21.16	51.93
2	27.88	53.88	17.11	40.49
3	17.95	35.18	26.76	61.54
4	29.55	58.30	15.55	38.66
5	21.11	40.79	31.69	63.58
6	20.65	36.37	27.19	65.05
7	2.74	8.55	7.90	26.51

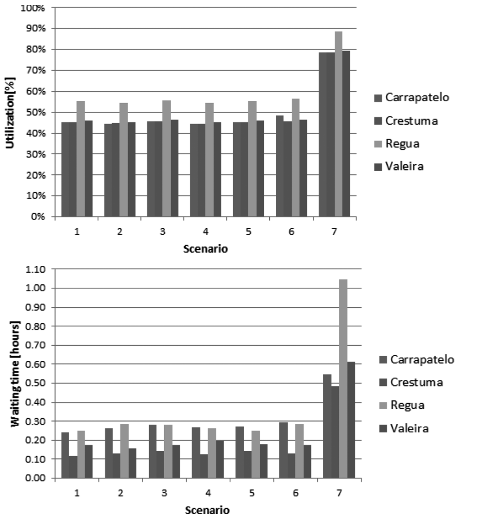

Figure 5. Lock utilization and average waiting time for lock.

6 CONCLUSIONS

A simulation model of a river/sea transportation system was developed. A number of feasible scenarios were specified and simulations corresponding to 5 year periods were carried out.

It was assumed that the river channel is dredged to ensure a depth of 4.20 m and that both terminals have no work schedule restriction. The current daytime only navigation restriction in the river was tested and revealed a big impact in the entire transport system and due to that the analysis was carried without this restriction.

The existence of concurrent traffic in the inland leg of the voyage was included in this simulation model. The cruise ships (the only traffic that was considered in this study) is a growing activity and is important to analyze the relation between the iron ore transport and this touristic activity.

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. For instance, adding one berth to the sea terminal only decreases the port time one hour which may not be a sufficiently large difference to justify the implementation of that extra berth. 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. The economical aspect together with the operational side will allow drawing more robust conclusions when deciding what the more suitable solution for this transport problem is.

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. This information will result in additional restrictions in the model, concerning the crossing and passing of ships along the river.

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Design optimization of a bulk carrier for river/sea ore transport

D. Merino da Silva & M. Ventura
Centre for Marine Technology and Engineering (CENTEC), Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal

ABSTRACT: This work presents a feasibility study of a river-sea bulk carrier for the transport of iron-ore from a new river terminal to a sea port on the Portuguese west coast. The objective of this study is to determine the optimum characteristics of the ship and service speeds. First the transport problem is described and the main design options are discussed. Next, the main components of the ship synthesis model, the voyage model and the optimization procedure are presented. Finally the results are discussed and some conclusions are drawn.

1 INTRODUCTION

The expected large annual production of an iron ore mine and its location close to a river is the motivation for the study of different transportation alternatives from its location inland until a sea port for export in deep-sea bulk carriers. In this work is analyzed the design by a river/sea bulk carrier for the transport of the ore from a terminal in the river down to the sea port.

The specification of a ship mission is the starting point of its design. In this case, the ship is neither a typical inland ship nor a regular seagoing ship. The inland leg of the voyage has a length of about 75% of the total voyage length and passes through four locks that allow the navigation with the existing difference of levels.

Several configurations can be adopted to this type of inland transport: a propelled motor vessel, a train of non-propelled pulled barges, or pushed barges. In the European inland waterways pushed barges have almost completely replaced the trains of towed barges because they provide a better maneuvering capability and require less labor (barges are unmanned). In the current case, the morphology of the river that needs locks to guarantee the navigation and the existence of a sea leg in the voyage introduce constraints that make the propelled vessel the obvious solution.

In this work are described the ship synthesis model, the typical round trip voyage model and the optimization procedure. Finally the results are discussed and some conclusions are drawn.

The relevant rules and regulations are identified and their applicability discussed.

2 SHIP SYNTHESIS MODEL

The concept of Ship Synthesis Model (SSM) dates back from the 70's (Reed, 1976), with the initial development of the Advanced Surface Ship Evaluation Tool (ASSET) a software provided by the Naval Surface Warfare Center and used for the evaluation of naval ship designs. 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 availability of a SSM also allows consistency among the feasibility studies due to the use of similar methodology and criteria built into the models.

The SSM is the sequence of numeric methods that is used to integrate a number of different aspects of the ship design (Fig. 1). Even with the continuously increasing power of computers and engineering software, the development and analysis of a large number of alternative designs is not compatible with the extensive use of first principle methods. So, 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. Nevertheless, the trend is to develop SSMs in such a way that the modules can be upgraded to more precise computations whenever they are available and/or when their usage is compatible with the time constrains for the intended study.

In the following section are described the components of the SSM developed for the river/sea ship design.

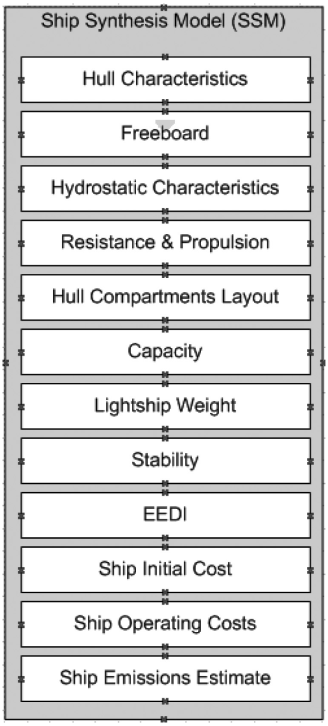

Figure 1. Components of the Ship Synthesis Model.

2.1 *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 (Fig. 2).

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 (Fig. 3).

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 bulkhead at a distance from the FP not less than 0.05 L or 10 m, whichever is less, but not more than 0.08 L, in a ship with no bulb (IMO, 2012a). However, SOLAS is not mandatory for ships designed for domestic voyages. Taking into consideration that

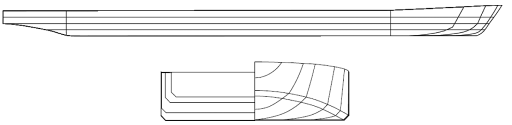

Figure 2. Lines and body plan of a possible hull form.

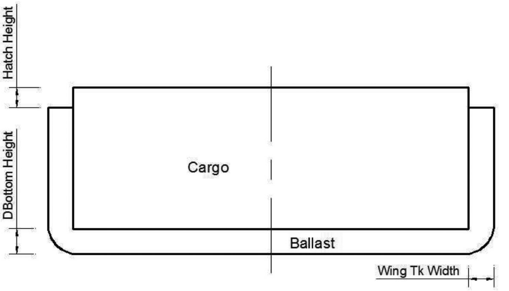

Figure 3. Sketch of midship section geometry.

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 0.4 L 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 0.4 L. Finally, the length of the cargo area is obtained by subtraction of these lengths from the ship's length.

2.2 *Freeboard*

An ore carrier is a displacement carrier, which means that due to its typical high values of cargo density, the volume for the cargo is not the issue. Therefore, the depth of the hull can be reduced as far as the resulting freeboard complies with the applicable ship safety requirements.

The International Convention on Load Lines (ICLL) applies only to ships engaged in international voyages, with a length larger than 24 meters (IMO, 2005). However, in the current case, the ICLL is adopted, in compliance with the flag authorities criteria.

2.3 *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 ore cargo density is about 2.2 t/m^3, which justifies an additional hull weight due to the required double bottom reinforcements. In accordance to the Common Structural Rules (CSR), sea-going bulk carriers can be classified in three classes, depending from the cargo density (IACS, 2012). For cargo densities larger than 1.0 the alternatives are the assumption of loading heavy cargoes only in alternate holds (Class BC-A), or in every cargo holds (Class BC-B). The CSR, however do not apply to ships with length less than 80 meters and so in this case all the cargo holds are assumed to carry ore.

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).

2.4 *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. In (PIANC, 1992) is made a classification of the water depth based on the ratio water depth/ship draught (h/T), shown in Table 1.

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). The F_{nh} is defined by

$$F_{nh} = \frac{V_s}{\sqrt{gh}} \tag{1}$$

in which V_s is the ship speed in (m/s), g is the gravitational acceleration in (m/s^2) and h is the waterway depth in (m).

Table 1. Classification of water depth.

Deep water	h/T > 3.0
Medium deep water	1.5 h/T < 3.0
Shallow water	1.2 < h/T < 1.5
Very shallow water	h/T < 1.2

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.

There is an extensive research work about the analysis and estimate of the squat sinkage because of its relevance in ship grounding. Such research includes numerical models validated by experimental tests and ship measurements, and semi-empirical formulas that are suitable for application in the initial ship design.

In this model, the bow squat was estimated in accordance with the Eryzlu formula (Eryzlu et 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

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

$$K_b = 1.0 \qquad \text{otherwise} \tag{5}$$

2.5 *Propulsion system*

The most common alternative of propulsion systems for this type of vessels are the four-stroke, medium-speed Diesel engine, a Diesel-electric system or, more recently, dual-fuel engines with the capability of burning either Marine Diesel Oil (MDO) or Liquefied Natural Gas (LNG).

In general, LNG is safer than Diesel. In case of a leakage, the gas evaporates due to the difference of temperature between room temperature and the liquid stage. The resulting mixture is not combustible at atmospheric pressure and so there are no direct damages to the ship or to the environment. LNG also has lower emissions then Diesel oil. 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%.

On the other hand, LNG cannot be stored in structural tanks as MDO. Generally are used cylindrical type tanks, which can be stored in containers for an easy replacement during bunkering operations. This arrangement not only requires more space but also this space must be in a convenient location close to the engine room, but near the deck for replacement.

The issues of the ship emissions in an environmental sensitive area and of 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 the LNG engine alternative, the storage of the gas requires some additional space in the ship. However, the current trend of lower prices of the LNG in comparison with the bunker fuel oils justifies the analysis.

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.

2.6 *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).

2.7 *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

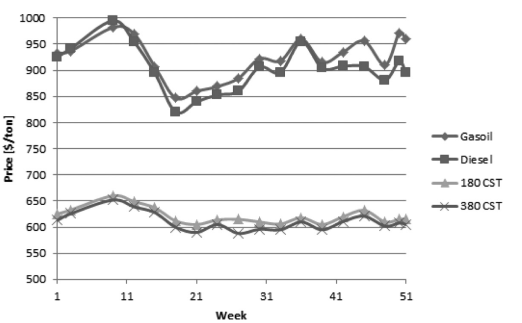

Figure 4. Fuel oil prices in 2013.

Table 2. Breakdown of ship running costs.

Cost categories	Cost items
Operating costs	Manning Stores & lubricants Repair & maintenance Insurance General costs
Periodic maintenance	
Voyage costs	Fuel costs Port costs Canal costs, lock costs
Cargo-handling costs	
Capital costs	Loan instalments Interest/dividends

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), as shown in Table 2.

3 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 domain model establishes the concepts within the scope of a problem and also the relationships between them. In the context of an object-oriented methodology, the concepts are represented by *Classes* and the relationships by *Associations*.

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* (Fig. 5).

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*, or a region where a different type of fuel must be used (environment protected areas) or there are different water depth characteristics (Fig. 6).

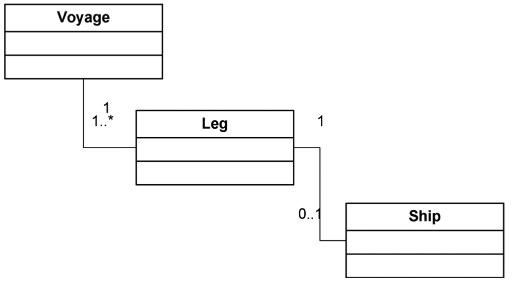

Figure 5. Main data classes.

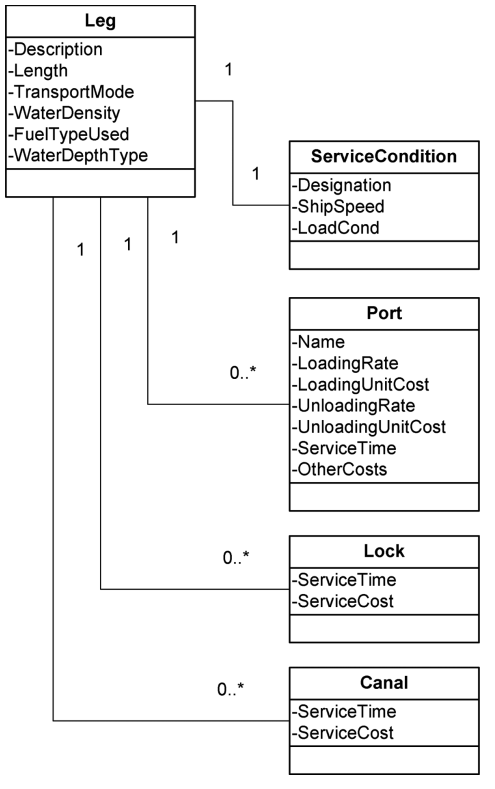

Figure 6. *Leg* class.

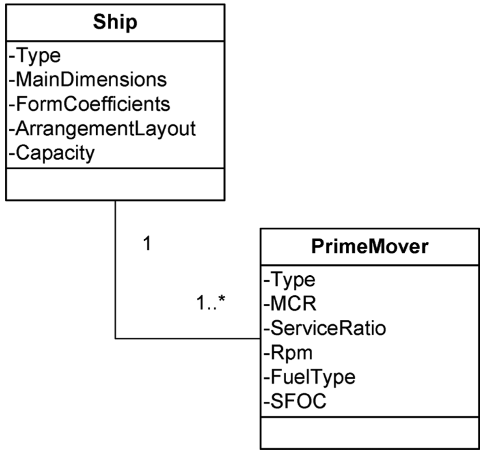

Figure 7. *Ship* class.

Each *Leg* is also associated to one ship *Service-Condition*, 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 4.

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.

In Table 5 are summarized the terminal characteristics assumed in this study.

Table 3. 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

Table 4. Physical limitations in river route.

Hull dimension	Limitation	Source
Length overall	Max. 86.0 m	Locks
Breadth	Max. 11.0 m	Locks
Draught	Max. 3.7 m	Locks
Air draught	Max. 7.2 m	Bridge

Table 5. 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 [$/ton]	0.0886	
Terminal fees [$]	$0.1961 \times GT + 0.1989 \times CWT$	
Service time [h]	0.5	1.0

4 DESIGN OPTIMIZATION

4.1 *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. Figure 8 shows that the results of the model, after the correction factor was applied, are more fitted to the real data. The model results are also in the same range as those of the Hoffman/Heusser formula (trend line) for weight estimate of inland vessels (Hekkenberg, 2013).

The results were also compared with the Michalski method but this method seems to understate the lightweight.

In the model the cargo capacity estimate is done based on the configuration of the midship section and on the cargo length, which depends from the lengths of the aft peak, engine room and fore peak tank (see 2.1).

To validate the cargo capacity estimation method the actual cargo volume was computed in a 3D model developed according to the hull form