Simulation of Short Sea Shipping based Intermodal Transport Chains

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ABSTRACT: This paper applies the discrete event simulation technique to model an intermodal transport chain, making use of maritime (Ro-Ro) and road transports. This type of supply chains is heavily affected by several uncertainties related with bookings and the performance of modal change terminals, land transport and maritime transport. These uncertainties combined, generally lead to transport reliability issues that create reluctance on logistic companies when choosing intermodal solutions over other possibilities. Intermodal transport has given proof of numerous advantages regarding environmental, economic, and societal matters. In counterpart, it is generally less time effective, associated also with fluctuations in the times of delivery.

A discrete event simulation model is developed to assess the overall reliability of the transport service, based on whether a combination of road and maritime transport or only road transport, for the cases where intermodal is unlikely to succeed. It was also modeled the fully-road based transport chain for the same transportation problem to compare both modalities.

The simulation model represents in detail the operation of ships in the route (including casualties like port strikes, mechanical off-hire, etc) and the traffic of trucks between cargo origins or destinations and respective ports. The schedule compliance is evaluated (under the many uncertainties), as well as the delays occurred on the cargo deliveries, the occupation of each “player” and the overall reliability of the system. A comprehensive assessment of the economic performance of the system is also carried out and conclusions are drawn.

KEYWORDS: Intermodal, Supply chain modeling, Discrete Event Simulation, Short Sea Shipping, Reliability.

1 INTRODUCTION

In Portugal the exported goods are mainly produced in the northern region. Shipments from Portugal to Northern Europe are mostly made by road whereas there is evidence that intermodal solutions are friendlier to the environment and, depending on the transport chains considered, freight transport costs can be lower.

Modal efficiency is a factor of utmost importance for the realization continental and intercontinental trade operations and the optimization of transport modes with large capacity is a vital issue. In Europe, there is still a lot to do to balance modal split since 71.7% of the freight transport is made by road, being Portugal above average with 84.1% European Commission (2019).

The CO₂ emissions from freight transport have been increasing in the last decades. Eurostat (2017) declares that in 2015 CO₂ emissions represented 33.8% of the total EU emissions1 while in 1990 these emissions represented 18.4%. In this logic, intermodal transportation is considered to have high potentials to support sustainability and energy efficiency. Intermodal transport could be defined as multimodal chain, made up of several different entities interacting with each other, linking the shipper with the receiver of the shipment by the “movement of goods (in one and the same loading unit or a vehicle) by successive modes of transport without handling of the goods themselves when changing modes.” - United Nations (2004).

Due to the environmental advantages and the potential to generate economies of scale Crainic et al., 2017; Demir et al. (2016), intermodal transport has emerged in the agendas of the scientific and political communities. A substantial number of solutions related wo the intermodal transport has been stimulated along the years, starting from 1992. Programs like PACT, Marco Polo I and II, Motorways of the Seas, etc have financed such innovative solutions. Also, in the roadmap set by the European Commission (2011) it is stated that 30% of road freight over 300 km should shift to other modes, friendlier to the environment, such as rail or waterborne transport by 2030, and more than 50% by 2050, facilitated by efficient and green freight corridors.

Aligned with this, countries in the center of Europe are increasingly regulation road haulage by stablishing new/resting time rules, minimum wages and cabotage protection enforcement. The volatility in fuel prices contributes to unreliable the economic return. Also, it is being fixed new tolls and being restricted the passage of freight vehicles in specific parts of the road in order to reduce traffic congestion, road deterioration, noise and pollution. In addition, bad weather conditions and social crisis (such as strikes and blockades like the yellow vests protests that started in late 2018) periodically delay road transportation services.

To comply with these circumstances that add cost an uncertainty to road freight transport, the study presented in this paper addresses the tactical problem of service network design for intermodal transport. In this case, a transport solution that includes a maritime link to ease the growing pressure on full-road based freight transportation. After it was identified a transportation demand to full on shipping cargo from a set of cities located in the north of Portugal to some others in Northern France, Belgium and Luxembourg, a network for the specific door-to-door transport problem was designed, from the point of view of a generic logistic company. It was also designed a unimodal transport chain, fully-road based, in order to evaluate the competitiveness between both chains.

The intermodal chain includes three legs: pre-carriage (road based), short sea shipping (Ro-Ro based) and on-carriage (road based), whereas the unimodal chain is fully-road based. A study like this would require statistical data describing the operations but, as concluded in the literature review and inquiring logistic

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1 Excluding international maritime (international traffic departing from the EU) and including international aviation.
companies and port terminals, this type of data is rare kept confidential. For that reason, it was considered data from Santos et al. (2018) for characterizing some of the operations. Nevertheless, the system is ready to, at any moment, receive a data replacement and accordingly, update the results.

For intermodal transportation, several studies have been made to evaluate technical and economic workability but mostly from the point of view of the decision makers for transport operations that prioritize cost and transit time over anything else, when making decisions. Although, it is necessary to analyze different parameters like service’s reliability, frequency, quality, and spare capacity availability. Competitiveness is making these parameters more relevant than before to the companies.

Due to the high complexity and high variability in transportation movements, especially when considering uncertainties, it is not an easy task (technically speaking) to use analytical models, such as linear or dynamic programing, to study and evaluate freight networks. Therefore, simulation was the method chosen to address the transportation problem since it can imitate the real behavior of systems by providing test bed for various experiments Kelton and Law (2000).

The problem depicts a cost-minimization objective and simultaneously intends to reach high levels of reliability. It was resorted to a commercial software of simulation to recreate the network designed and test several transport solutions – scenarios. Assuming plausible and consistent specific changes in the values of input, all steps are measured and analyzed to get a better understating of how the system behaves. Simulation models can answer “what-if” questions, especially in complex and dynamic networks which behavior is so hard to predict. There are two groups of simulations, discrete and continuous Banks (1998), and this transport system analyzed here fits well with a discrete system, since entities change state at distinct moments in time due to uncertainties.

From using simulation, it is expected to get considerable benefits, such as:
- Test the transport system under study before its implementation and/or acquiring the resources.
- Infer about how or why numerous phenomena occur and test their feasibility.
- Time can be compressed or expanded, granting the possibility to speed up or slow down a phenomenon under study.
- Insight on which variables and/or resources are most important to performance and how these interact with each other.
- Identify bottlenecks.
- New adjustments can be done at any time, like future new input values or uncertainties.

It was not found in the literature a discrete event simulation study applied to intermodal transport, what brings a character of innovation in this field. This study approaches both intermodal and unimodal exclusive transportation, comparing their pros and cons and measures to improve efficiency of such transport chains are proposed.

1.1 Objectives and Structure

The objectives of this work are the following:
- Develop a discrete event simulation model of intermodal transport operations that include a short sea shipping leg and pre- and post-haulage road distribution legs throughout the hinterland of the connected ports.
- Evaluate intermodal freight transport time reliability.
- Determine the conditions that lead to an effective solution at a minimum cost.
- Evaluate the competitiveness between unimodal and intermodal transport solutions for the proposed transportation problem.

This paper is organized in seven sections and respective appendices. Section 1 is the introduction of the topic to be discussed the related background and including the goals and structure of the work. Section 2 contains the literature review of the works of up until today, as well as the adopted theories from the information gathered. In Section 3, it is presented the description of the transportation problem, modal services approaches and its characteristics. It is also briefly described some uncertainties present on this type of transportation problems that were included in the study developed. Section 4 details the methodology, starting a brief introduction to the simulation lexicon and specific ARENA simulation software particularities. Then, it is structured the implementation of the problem for both modalities, followed by three subsystems recreated in ARENA. To end this chapter, model verification, validation and evaluation is approached. Section 5 presents the case study definition, specifying all the characteristics of the transportation problem, including the uncertainties. The costs involved are also specified in this chapter and distinguished between the two transport solutions (intermodal and unimodal). Section 6 shows the results obtained for each configuration simulated as well as the methods used to verify and validate the implemented model. The results are also analyzed, in order to produce credible and concrete conclusions for this study. The last section contains the main conclusions taken from the work produced, along with some recommendations and suggestions for future work to be developed.

2 LITERATURE REVIEW

Intermodal freight transportation can be defined as the transportation of cargo from its origin to destination, making use of at least two transportation modes. The transfer from one transportation mode to another is performed at an intermodal terminal. The main characteristic of intermodal freight transportation is that the cargo is not handled when changing modes, it is only moved in one loading unit or vehicle. Nevertheless, different types of packaging may be present such as containers, boxes, pallets, swap bodies, semitrailers, etc United Nations (2001). In sum, the concept is to use the strengths of different transport modes by combining them in one integrated transport chain.

Intermodal transportation is generally recognized as the pillar of international trade and essential for the globalization of the economy. It plays a big role in modal change, also promoting the utilisation of more environmentally friendly water and rail-based transportation modes to the dedicated rail-based container and trailer transportation systems in numerous parts of the world.

Besides, intermodal transportation is in the basis of new emerging operational and business models for transportation and logistics, such as Physical Internet, City Logistics and Synchronomodality, that aim to simultaneously achieve
environmental, economic and societal goals [Zhang and Pel (2016)].

The development of the intermodal transportation in these roles creates a great impact in several transportation modes and intermodal transfer terminals, which also involves a wide range of decision makers, operations and planning activities. All these aspects combined make the intermodal transportation highly complex, creating the necessity of having a monitoring system for these activities. Nowadays, it is available a wide range of models and methods to build and manage operations and adapt alternatives to achieve sought levels of cost versus quality of service versus environmental and societal impacts. In this context, simulation plays an important role since, on the one hand it allows to represent the behaviour of a given transportation system, and on the other hand, to estimate its response to diverse changes in its environment. Simulation allows to detect bottlenecks, explore “what if” questions, fully understand of how the system really operates, etc.

Despite the literature being abundant on transport time reliability and its metrics in general for road transport, there is not much for simulation of intermodal transport systems, specially using Short Sea Shipping (SSS). Also, the impact of long-haul transportation as distinctive element of intermodal chains is under researched [Erfurth and Bendul (2017)].

In the scarce literature, the most abundant one regards the economic efficiency of intermodal networks resorting to heuristics, like Flodén (2007) and Jensen (1990). Sambracoss and Maniati (2012) and Trant and Riordan (2009) studied the technical and economic feasibility of intermodal transport solutions across specific corridors between European periphery and Continental Europe or within the same country, both aiming at providing a viable solution towards the promotion of SSS in the transport chain between mainland ports and with the utilization of Ro-Ro ships for part of the intermodal transport. Wiśnicki et al. (2017) presented a research focusing the development of European intermodal transport system, proposing a strategy to develop the existing Polish intermodal transportation system, that is still in its early stages, according to the authors. Santos and Guedes Soares (2017a, 2017b) presented two studies dedicated to the Portuguese case, considering the utilization of roll-on/roll-off (Ro-Ro) ships. In the first study, the transport demand for a transport solution that includes Ro-Ro ships and road haulage (for pre-carriage and on-carriage), was estimated for various combinations of ship speeds and freight rates, taking the perspective of the shipper (or logistic company or forwarder) and using as decision parameters the transit time and cost. In the second study, a methodology was developed to identify the Ro-Ro ship and the required fleet size necessary to meet the estimated transport demand, allowing the identification of the optimal point of operation (ship speed and freight rate), taking the point of view of the shipping company rather than the shipper.

The second most relevant topic found in the literature regard the emissions from transportation systems and how intermodality lowers the ecological footprint, as approached by Demir et al. (2016) and Hanoka and Regmi (2011) and Jemai et al. (2012) and Roso et al. (2009).

Related with transport time reliability Zhang et al. (2018) presented a method that allows to estimate the change in transport time reliability of an intermodal transport chain by changing parts of the chain. Whereas considering uncertainty in conventional methods such as linear or dynamic programming can lead to problems due to high number of possible configurations, simulation can be used in this context since it can recreate the real behaviour of systems by providing ground for various experiments. Although, there is few in literature on simulation of intermodal freight transportation, as approached by Hrušovský et al. (2016), Kelle and Jin (2016), Preusser (2008), Reis (2014), Reis and Macário (2008) and Song et al. (2013).

Overall, research in the field of simulation of Ro-Ro terminals, especially when integrated in door-to-door intermodal transport chains, still requires further development.

3 DESCRIPTION OF THE TRANSPORTATION PROBLEM

As mentioned in the previous section, simulation models of door-to-door intermodal transport chain are largely absent in the literature but could be used to assess the reliability and other parameters of these chains. One such model will be presented in this section, which considers typical transport operations of a logistics company that needs to send general cargo (in containerized form) from Northern Portugal to Northern France. This company has a set of customers (exporting companies) in Portugal (from which the company collects cargo) and these customers send cargo to typical locations in Northern France. The cargo unit will be considered equivalent to a full truck load or a 40 feet container. Currently, the mentioned logistic company uses the roads to carry the cargo, but it is experiencing increasing problems for using the EU road system, due to the restrictions mentioned previously.

The logistic company is now studying the possibility of using a Ro-Ro cargo liner service, currently in operation between a port in Portugal and a port in France. In addition, it would have to use a fleet of trucks in Portugal to take the containers to the port and the same in France (respectively pre-carriage and on-carriage).

The company is, however, resisting to use this Ro-Ro line as, in general, short sea shipping experiences problems with reliability and this might produce unacceptable delays in cargo delivery. The company usually accepts contracts with time windows for delivery in different locations. Therefore, it needs to estimate the number of failed deliveries per year when using the intermodal solution, in order to compare the numbers with its extensive experience in using the fully unimodal road-based solution. The reliability of the intermodal or unimodal transport solutions needs to be evaluated under the influence of several unpredictabilities, which will be enumerated and characterized using probability distributions in the next sections.

3.1 Road Service

The road service is taken as the part of the transport done by road, making use of a truck and a driver for each cargo unit transported. Road transport is the most common transportation method, and it has many dimensions, from the door-to-door transport present either in big cities or in small villages, to the long-haul international freight transport. The abundant existing configurations of road transport chains require different structures to operate, change in complexity as well as in the cost structures involved. There are identified many issues in road transport, such as the lack of resources efficiency involved in its
operation (one driver and one truck for each cargo unit transported) and it is considered a big contributor for the carbon emissions in our planet. Although, the key factor that still justifies its massive utilisation is the transport time efficiency and reliability since it is taken as the less risky to fail a delivery on time.

There is, though, an uncertainty compromising road service which is extreme weather conditions that are most common in northern Europe, regarding snow and consequent road closure. It is assumed that due to bad weather the roads close for 24h, twice a year. Although, these events only occur in winter, when weather is rougher. Hence, the system will consider a probability density function to trigger the bad weather events.

3.2 Short Sea Shipping Service

Short Sea Shipping (SSS) is a term used by the European Commission referring to the maritime transport of people and cargo between ports located in the Member States of the European Union. The main particularity of this transport is the small distances travelled between ports, when comparing with the usual intercontinental shipping lines. SSS came from the necessity to develop a solution to complement and/or alternate the usual intercontinental shipping lines. SSS came from the necessity to develop a solution to complement and/or alternate road transport, as a way of minoring the road infrastructures saturation.

The SSS service involves a sea leg connecting the ports of Leixões, Portugal and Le Havre, France (both fitted with a Ro-Ro terminal) with a Ro-Ro vessel, that will transport the semi-trailers from Portugal to France. To complement the SSS service, there are 6 road legs in Portugal connecting the origin cities and the port of Leixões and 6 road legs in France connecting the port of Le Havre with destination cities.

A maritime shipping company is providing the maritime connection on a weekly basis and it is considered a fixed price for the freight transport on the sea leg. The logistics company represented here has facilities in both regions, that are located near the corresponding ports. Until there is a pair truck-driver available to take out a cargo from/to the port, those goods are held in the respective cargo origin (in Portugal) or at the port of Le Havre, if that is the case.

The ports and shipping line operations are affected by uncertainties, considered in the simulation model, which cover and approximate reality. The first of these uncertainties is related to the fact that weather can turn out to be a major problem for transportation services, affecting all types of transport. In maritime transport, it can force the ports closure and in very singular situations, restrain the ship voyage. So, it is assumed that due to bad weather the port closes temporarily, for each bad weather event. Although, these events occur in winter, when weather is rougher. Hence, the system will consider a probability density function to trigger the bad weather events.

Like bad weather events, there are also ship mechanical failures and port strikes, occurring randomly along the year, following uniform distributions (different from each other). A mechanical failure makes the ship is inoperative temporarily and to make sure the failure affects the service, these events are set to occur at the instant of departure from Leixões, corresponding to last minute technical problems.

Strikes in both ports occur also twice per year, randomly (uniform distribution). These events imply the non-departure of the ship if they coincide and the port inability to accept or release cargo, depending on the port it happens. Since these events are unpredictable, it is not possible to take measures in anticipation, compromising the cargo shipment. Also, apart from the delays these events can create, the queues formed when waiting for the normality to be restored imply an extended occupation of the resources, namely trucks and drivers.

Both ports work all weekdays from 8:00 am to 0:00 am, thus, if trucks arrive outside of this schedule they must wait. Although, the system is designed to predict the time of arrivals so that the trucks and drivers are only assigned when they are expected to arrive within the port working period. This way it is avoided unnecessary waiting and misuse of resources.

The ship departs from port according to a fixed weekly schedule. The model allows a weekly frequency or multiple departures per week, always at a fixed time. However, in reality, ships frequently get delayed and so, departure delays were included. The delays are not expected to be very long (1 to 5 hours), although they are expected to be more predominant in Autumn (high season).

The ship generally accepts last minute cargo up to approximately 3 hours before departure time, otherwise, cargo is forwarded to unimodal transport. Last minute bookings mean bookings made in the day (24 hours) before the scheduled departure time. Although, when transport demand is higher, the chances of a last-minute booking to be accepted are way lower and that was taken in consideration as well.

The ship service speed is generally constant, but in reality, it is uncertain due the weather conditions and were used two ship velocity discrete distributions. The reason to discriminate is the presence of rougher weather conditions in winter, what affects ship speed performance, reducing the average velocity in that period.

3.3 Summary of uncertainties

Considering the description of the operations in previous sections, the uncertainties involved in this simulation model are:

- Ship departure time (delays in departing for some hours),
- Availability of cargo space in the ship (especially in high season),
- Bad weather in ports (closing down the ports for some days in Winter),
- Bad weather in road (closing down certain links for some days in Winter),
- Ship technical off-hire (breakdowns),
- Port and terminal strikes,
- Ship speed (decrease in speed in Wintertime, especially),
- Time between customer bookings and the beginning of the delivery window in destination,
- Spatial and temporal distribution of actual bookings,
- Distribution of bookings throughout the year (seasonality),
- Road speed (defined on a link-by-link basis, with rush hour in certain links),

3.4 Key Performance Indicators

The Key Performance Indicators (KPI) defined are intended to express the desired outcome fulfillment and how much and how the actors in the system influence its performance at the most relevant levels.

One of the outcomes that has made the difference when choosing the transport modes by logistic companies, like this one acted out here, is the reliability of the transportation. In other words, the percentage of successful deliveries, within a specified time window. Even if a not so effective transport system turns out to be cheaper for the logistic company, clients tend to prefer reliability over (a not substantially different) price. Nevertheless, cost is a main outcome to be considered, and so, the total costs of the transport solutions are also to be measured and evaluated.

Even with transport systems reliability (successful deliveries) being a major performance indicator for the problem under study, the celerity of the transport is also important to be measured, since it may limit the type of goods to be transported. Also, as it is intended to make the most efficient utilisation of the players in the system, the utilisation of trucks and drivers during the 24h before ship arrival are indicators to be measured, as well as during the whole high season (September to November).

Summarizing, the KPI to be measured while simulating the system, or calculated based on the simulation results, are the following:

1. Reliability of the transport solution expressed as the percentage deliveries within time window in destination cities per year,
2. Total cost of logistic company operation per year, split between fixed and variable costs,
3. Average transit time per pair origin-destination per year,
4. Average utilisation of the truck fleets and drivers during the 72 hours upon ship arrival.
5. Average utilisation of truck fleets and drivers during the high season (critical period).

4 SIMULATION MODEL OF THE TRANSPORT PROBLEM

As mentioned before, it was through simulation that this problem analysis was approached, making use of ARENA v14.0 simulation software. The simulation, as method, brings many advantages since it is intended to mimic the behavior of the real-world system over time, reacting to change and other inputs in a similar way as a real system would. Simulation models can answer “what-if” questions, especially in complex and dynamic networks which behavior is so hard to predict.

Altiok and Melamed (2007) describe the main principles of modelling using this particular software, while Figure 2 represents summarily the general lay-out of the simulation model, that is, a brief sequence of events from cargo generation to delivery at destination. The cargo is generated using uniform distributions which are different for each season, having the peak in Autumn, from September to November. Based on average values of velocity distributions, ship schedule, drivers resting periods and distances from origin to destination, the system estimates if each cargo unit generated can be admitted for intermodal transport, giving preference for the truly intermodal component of the intermodal system (which comprises a unimodal possibility as back-up). In other words, if a cargo is expected to be delivered within the time window using the intermodal solution it is forwarded by intermodal transport, otherwise it is forwarded by truck (unimodal transport).

In case intermodal transport may be used, the model goes through Intermodal Sub-model 1, the port of Leixões and, then, Intermodal Sub-model 2, which includes the port of Le Havre and subsequent on-carriage operations to the final cargo destination.

Once the cargo has been admitted for intermodal transport, it enters Intermodal Sub-model 1, which is represented in Figure 3. To pick the cargo up, it is necessary that a truck and a driver are available. If so, the truck speed is assigned and the voyage to the cargo origin starts. When the truck arrives, the return voyage is starter immediately to take the cargo to the port of Leixões. Then, the truck goes to the truck park immediately, unless it is necessary to perform maintenance/cleaning activities, and after the potential daily or weekly rest breaks, the driver is set as available again. When another cargo unit is generated in the system, the same procedure is repeated.

Figure 2 - General layout of the simulation model.

Figure 3 - General layout of Intermodal Sub-model 1.
When the ship arrives in the port of origin Intermodal Sub-model 2 is initiated. Figure 4 shows the details of this sub-model. All cargo units in the port are assumed to be ready to be loaded in the ship when it arrives. The ship arrival is scheduled for once every 7 days, which means that the ship is set to arrive always at the same hour of the same day of the week (fixed schedule). When the departure is possible, the ship speed is calculated from its random distribution and the voyage starts after the potential departure delays.

![Figure 4 - General layout of the simulation Intermodal Sub-model 2.](image)

The unloaded cargo units are sorted by shipping priority, making it possible that cargo is unloaded later but actually is shipped from port first. The truck is requested to pick-up a cargo only if it is not expected to deliver it before the delivery date, otherwise the cargo is stored at the park longer. When the truck is requested, if there is also a driver available, the truck speed is calculated from the respective random distribution and the voyage immediately starts. If necessary, the driver will stop to take a daily rest on his way to destination or on the way back, which means that the daily rests may affect the time of deliveries. Like what happens in the end of Intermodal Sub-model 1, when the truck and driver come back, the truck goes to the truck park immediately, unless if it is necessary to perform maintenance or cleaning activities and the driver is set as available again, after the daily or weekly rest breaks. When another cargo unit requests a truck, the same procedure is repeated.

If cargo is forwarded via unimodal transportation, the system enters the unimodal sub-model, that is illustrated in Figure 5. By entering in this submodel, the system estimated how long the voyage will take to destination and when it is expected to be delivered within the time window, the system requests a truck from the Portuguese truck fleet and a driver of international long-distance transportation.

![Figure 5 - General layout of unimodal Sub-model.](image)

If both truck and driver are available, the voyage to origin starts immediately. The entities driver, truck and cargo are merged and the voyage to destination is initiated. The distances traveled are long and the driver can only drive for a maximum of 13h in a row, according to the European legislation European Parliament and Council (2006), which requires the driver to pull over and rest for 11h, as much time as necessary until arriving to destination. When at destination, if the deliver is within time window or after, the cargo is dropped and the voyage back to Portugal starts immediately. Otherwise, all entities are held until entering the time window.

After dropping the cargo at destination, the return voyage begins, stopping as to rest when necessary in the way back to Portugal. In a real context, this type of logistic companies usually tries to book a freight back in order to monetize the return voyage. Although, since the services made returning to Portugal are not under study and its characteristics are not known or predictable, these are not taken into consideration in the simulation.

When back in Portugal, at the company’s facilities, both truck and driver conditions are checked and if possible, set as available for another service. Otherwise, trucks undergo in maintenance and cleaning operations and/or drivers enter in daily/weekly rest periods.

4.1 Number of replications of simulation

It was observed that with 20 iterations the system is perfectly stabilized, that is, the calculations computed for the reliability obtained would not change significantly with further iterations. Figure 6 shows the reliability obtained depending on the number of iterations and supports this conclusion.
4.2 Validation of the Model

The validation of a model is not an easy task as it is necessary to validate three parts of the model: the underlying conceptual model, the translation of the conceptual model into a computer model and the actual computer model Lehman (1977). The first one was defined having in mind similar transport solutions in Europe, regarding Intermodal Freight Transport and making use of SSS. The second one was extensively compared with the relevant literature.

The actual computer model validation was decomposed on three steps: verification, validation, and evaluation. All steps were performed and it is concluded that the model is well adapted for this problem and for the input data set, the analysis conducted in the next sections of this paper verifies that the requirements are met.

5 CASE STUDY DEFINITION

The general characteristics of the transport problem and the type of uncertainties involved have already been listed in sections 3 and 4. This section will define in more detail the uncertainties involved in the transport operations.

As intermodal transport is expected to be much more lagging, the unimodal solution is used when the system (logistic company) estimates that the cargo will not arrive within the time window, using the intermodal alternative. This happens, as previously mentioned in section 3, due to the ship’s weekly schedule and to ship lower velocity when compared with the road alternative, leading to higher transit times. Hence, cargoes booked at short notice or long before next ship arrival will very unlikely be admitted for intermodal transportation and so, a probability density function is used to decide on this matter (seasonality effects were considered).

5.1 Transportation routes definition

It was considered the same sea leg as Santos et al. (2019) between Leixões and Le Havre and the same road legs as Santos et al. (2020) for intermodal service, connecting the cargo origins and destinations with the ports of Leixões and Le Havre, respectively. In Figure 7 it is represented the road legs at the origin country.

For the unimodal fully road-based transportation, the road legs were defined in a similar way, resorting to Google (2) and are illustrated in Figure 8.

5.2 Characterization of uncertainties

Firstly, the occurrence of bookings throughout each month is uncertain. There is also a seasonality effect with a peak in the Autumn. In Figure 9 it is specified the number of pairs origin-destination generated throughout the year.
The origins of cargo in Portugal are 6 cities at known distances from the port. As it can be seen in Figure 10, two different speed distributions are used, one for intermodal road transport and another one for unimodal (fully road based) transport, with 75.7 km/h and 77.6 km/h of average speed respectively. The reason for the slightly lower speed in intermodal transportation (pre-carriage and on-carriage) is the fact that in the access to ports congestion normally exists and the speed distribution tends towards smaller values.

Cargoes have a time window for delivery (characterized by day and time of beginning and end, separated by 48 hours) at the destination cities and are characterized by a booking date which is the departing point for carrying out the transportation. The bookings accepted by the logistics company occur with a random distribution (user specified) between the 4th day and the 9th day before the beginning of the delivery window in destination, as shown in **Error! Reference source not found.**

Upon delivery of the cargo in the port or in the cargo final destination, the truck returns to the company’s facilities in the region (located not far from each port). After every 5000 km travelled, each truck goes out of service for 24 hours to perform cleaning and maintenance activities.

Uncertainties considered in the simulation model also cover certain aspects of the operation at the port terminal and the ship. First, the port (and consequently the terminal) is closed due to bad weather two times per year of one day each, which occur according to a random distribution over the period between November and March, presented in Figure 12. The ship is inoperative two days per year (off-hire for technical reasons) and this event will occur randomly (uniform distribution) over the year. Strikes in the port occur twice per year also randomly (uniform distribution) over the year. This implies no departures will happen over these days (bad weather or strike) if the days coincide with ship departure days. The containers will have to wait for the ship to be ready to sail (the ship departs one day later than scheduled day). Bad weather and strikes are known with 24 hours anticipation, so it is not possible to plan in advance for these events. When an off-hire event (due to technical reasons) happens, this is only known right at departure time and corresponds to last minute technical problems.
The ship generally accepts last minute cargo up to 3 hours before departure time (truck needs to arrive at least 3 hours before departure time). In Autumn the ship is generally full and 90% of times it is not able to take last minute bookings (cargos). During the rest of the year, 90% of times the ship is able to take last minute bookings. Last minute bookings mean bookings made in the day (24 hours) before the scheduled departure time. Time delay between trying to book space in the ship and the booking time in the logistics company is fixed at 6 hours.

The ship’s service speed is generally 15 knots but, in reality, it is uncertain, according to the distributions shown in Figure 14. The distributions vary according with the season of the year. This variability in ship’s speed leads to variations in the sailing time between ports. The values adopted for these distributions are in line with the operational practices of a regular service currently in operation.

With the upper mentioned methodology it was avoided the simulation of every possible configuration of an intermodal solution that would be discarded anyways, due to quantities unbalance.

6.1 Intermodal

The configuration that outputted the best relation between cost and reliability obtained was configuration number 14, composed as specified in Table 1. This configuration’s reliability output was 96.85% and the total cost of 6,271,245€.

Table 1 - Optimal intermodal configuration

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Note: Entity type 1 (E1) – Intermodal drivers (PT based); Entity type 2 (E2) – Unimodal drivers; Entity type 3 (E3) – Intermodal drivers (FR based); Entity type 4 (E4) – Trucks (PT based); Entity type 5 (E5) – Trucks (FR based)

In Figure 15 it is represented the variation in late delivery penalties applied in each configuration with the intention of establishing a possible relation with both total cost and reliability, also representing the number of late deliveries implied in each configuration.

6 NUMERICAL SIMULATION RESULTS AND DISCUSSION

It is noteworthy that the system needs all the five entity types to work effectively and an absence or not enough quantity of an entity type creates bottlenecks. Also, it is important to take the most out of these entities so the balance between quantities of each type lowers the costs, increasing the combined utilisation ratio. It is possible to record the utilisation of each entity, by allocating to each one a resource, and by analysing it, it is possible to identify which one is creating a bottleneck. Thus, the methodology followed to reduce the number of configurations was to spot the entity type being overloaded and increase the quantity of that resource between 1 to 5 units (depending how far from the desired were the KPIs) in the next simulation. This methodology was repeated while there were bottlenecks still being found and the reliability of the transport time was still much below the required. When the outcomes were getting closer to desired, the changes in entity quantities were of one unit of one entity type, for each configuration. Reducing or increasing the number of resources, the transport time reliability of the system changes, since it relies on the number of cargo units delivered within the time window.

Figure 14 - Distribution of average ship speed in summer and winter.

5.3 Characterization of logistic company costs

The simulation model allows the cost calculation of the logistic company when using this intermodal solution. The cost structure of the logistics company is composed of its internal costs due to the operation of a fleet of trucks with the corresponding drivers. Complete costs of these fleets are considered to be the capital costs, fuel costs, tolls, insurance, driver wages, maintenance, road circulation taxes, following the values given in E. Tzannatos, S. Papadimitrious (2014) and Sambracos and Maniati (2012). The fleet of trucks is fixed in each simulation but the effects of variations in its size in terms of costs and reliability of the transport solution may be evaluated.

The ship costs incurred by the logistic company take the form of a freight rate per container, charged per voyage, plus a bunker allowance factor (BAF) indexed to marine fuel cost. The late delivery of cargo in destination cities has associated penalties of 400€ per day of delay. The anticipated delivery is not possible, making it necessary for the truck to wait in the port of destination before taking to the road on time to deliver the cargo unit within the delivery window.
Configuration 14 was the solution that generated lower total cost simultaneously fulfilling the reliability requirements. It was tried to improve the combined system outcomes by reducing the number of penalties applied but the investment in the increase of entities was not paid off by the savings in late delivery penalties. Configuration 9 is an example of that since regardless of the reliability improvements, the total cost increases prevail. It is also evident that a full reliability of 100% is not possible to achieve since there are events affecting the service that are not under control of a logistic company and cannot even be predicted, such as technical off hires, strikes, road closures due to bad weather, etc.

Configuration 14 also turns out one of the best results regarding the average transit time between a pair origin destination, that in this case it was selected the Guimarães-Paris as sample, both for the intermodal and unimodal solutions. This is a good indicator of performance, meaning the system is making the better possible under the conditions set.

The utilisation of trucks in France in the 24h after ship arrival is very high (close to 1), as observed in the utilisation plots shown in the dissertation for configuration 14. This indicates a very efficient use of those entities.

A lower utilisation of trucks in Portugal in configuration 14 is actually a good indicator, since at this time, intermodal transport should be the one being used to ship cargoes and for that reason, trucks are not being used by the full-road alternative, what decreases the utilisation.

6.2 Unimodal

The cargo transportation from an inner city in Portugal to another inner city in Northern France is not possible to do only by ship, but it can be done only by road, as it is of general knowledge. Thus, it is also interesting to evaluate the behaviour of the system described but only using road transport and afterwards compare the outcome with the intermodal solution. The configuration that outputted the best relation between cost and reliability obtained was configuration number 14, composed as specified in Table 2.

The higher number of trucks and drivers necessary to transport every cargo by road almost triples and despite the absence of a maritime freight transport cost, unimodal transportation turns out much more expensive.

In Figure 16 it is represented the variation in late delivery penalties applied in each configuration with the intention of establishing a possible relation with both total cost and reliability, also representing the number of late deliveries implied in each configuration.

The conditions that outputted the best relation cost-reliability were the ones of configurations 17 and 18, ending on being selected configuration 18 as the best solution for the transport problem under study.

Configuration 18 outputs one of the best results regarding the average transit time between a pair origin destination Guimarães-Paris and simultaneously make a very efficient use of both drivers and trucks, close to 1 in the high season of the year.

It is also clear that, independently of the number of drivers and trucks, it is not possible to reach a reliability of 100%. That is explained by the existence of events that compromise service, such as bad weather conditions, strikes in the ports, and ship technical off hires. Hence, regardless of the size of truck fleets and number or drivers, there is always unpredictable situations that compromise service that logistic companies cannot control.

7 CONCLUSIONS AND RECOMMENDATIONS

This dissertation has presented a discrete event simulation model of intermodal transportation in supply chains, using a ro-ro ship for the short sea shipping (SSS) leg of the transport operations. The model tries to recreate reality in many ways and, accordingly, contemplates the possibility to still resort to full road transport (unimodal) when it is clear that the intermodal solution will not lead to a successful delivery (without delay). The intermodal transport model performance is compared to that of a fully unimodal transport model, which represents the operations of most logistic companies nowadays. The simulation models were developed using a commercial software package – ARENA simulation v14.0 – and were applied to the study of transport operations of a generic logistic company that ships cargo from Northern Portugal do Northern France, Belgium, and Luxembourg.

The reliability of each transport solution was measured, separately and combined, when the sizes of the truck fleets and the number of drivers both in Portugal and France are modified. Both transport solutions are compared, and their respective pros and cons ascertained. Costs implied in the operations of both transport solutions are quantified and deeply analysed, with exception to the maritime transport, that is considered to be subcontracted at a fixed price and so, its cost structure is not approached here.

It is considered many uncertainties to imitate real world, such as the demand for transportation over the year (affected by seasonality), the pairs origin-destination, strikes, bad weather constraints, etc. The model results show that it is possible to use
it to quantify the truck and driver quantities necessary to reach specified levels of reliability of the transport operations. In this case, it was set a minimum for reliability of 95% and for both transport solutions (intermodal and unimodal exclusive), this requirement was fulfilled.

Under the assumptions of the current model, for the transport solution using intermodal transportation, the minimum total cost of the system occurred for resources such that the reliability was under 95% (of 91.34%), which cannot be considered as an admissible transport solution. However, the second lowest total cost obtained was for a configuration that largely fulfilled the reliability requirement, reaching 96.85% with a total cost of 6.27 million euros. The minimum reliability was an assumption and it needs to be ascertained if, from the perspective of a typical logistics company, the reliability of approximately 95% is indeed acceptable for the customers.

For the unimodal transport solution, the minimum total cost of the system occurred under conditions that outputted a reliability of 99.18% with to a total cost of this transport solution of 10.98 million euros. It was possible to achieve higher reliability results but with a total cost increase as consequence.

Like in the real world, it is not possible to reach a full 100% of reliability, since there are events affecting the service that are not under control of a logistic company and cannot even be predicted, such as technical off hires, strikes, road closures due to bad weather, etc.

By comparing two configurations of intermodal and unimodal transportation with the same reliability output and under equivalent conditions, it is concluded that intermodal transportation outputs a clear economical advantage of about 30%.

The simulation model also allowed an analysis of the impact of the different set up details in the numerical results. For example, it could be expected that the conditions that output the best reliability-cost relation would have unimodal transportation as the more reliable, but it was not. Probably with a narrower delivery time window, the reliability of the intermodal service would decrease considerably since the time of arrival is much more spread within the time window than in the unimodal solution. Also, the level of uncertainties related to ship and port operation needs to be better tuned with real world data.

Numerous recommendations for further studies may be made, but the one considered the most interesting one is the use of real data from logistic companies and port and terminal operators for the many inputs used, such as, truck speeds, cargo demand over the year and geographical distribution, delivery time windows, ship velocity, etc. This would enable a greater degree of similarity with the real world to be obtained, allowing companies to investigate which potential specific measures would create better services. Another action that could be taken to improve the model resemblance with reality could be the upgrading of the model with other uncertainties suggested by practice.

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