Simulation of Short Sea Shipping based Intermodal Transport Chains

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ABSTRACT:

Hereby it is applied discrete event simulation techniques to model an intermodal transport chain, making use of maritime (Ro-Ro) and road modes of transportation. 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 is used, 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 events 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 entity and the overall reliability of the system. A comprehensive assessment of the economic performance of the system is also carried out and several conclusions are drawn, being the most relevant one, the obtained economic advantage in 30% in the intermodal service, for the same levels of reliability and under equivalent conditions in both services.

Keywords:

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

RESUMO:

Nesta dissertação é apresentada uma simulação de eventos discretos para recriar uma cadeia de transporte que faz uso dos modos de transporte rodoviário e marítimo (Ro-Ro). Este tipo de cadeias de abastecimento são fortemente afetadas por inúmeras incertezas relacionadas com as reservas e a performance dos terminais de troca de meio de transporte, bem como do transportes rodoviário e marítimo por si só. Todas estas incertezas combinadas geralmente levam a baixas de fiabilidade, que criam alguma relutância às empresas logísticas no momento de escolher o tipo de transporte a contratar. Mesmo tendo o transporte intermodal já dado provas, em inúmeros casos de estudo, de ser mais vantajoso em termos económicos, ambientais e sociais, tem a contrapartida de ser menos fiável no que respeita ao cumprimento dos prazos de entrega das cargas.

Um modelo de simulação de eventos discretos foi então desenvolvido para aferir a fiabilidade global do sistema de transporte modelado, que tanto faz uso do transporte intermodal como do unimodal, para as unidades de carga que se preveem não ser entregues com sucesso via intermodal. Foi também modelado um sistema em tudo igual, mas que exclui o transporte marítimo, fazendo uso apenas do transporte rodoviário, de maneira a poder comparar a solução intermodal proposta com o típico transporte mais comumente usado.

O modelo de simulação representa em detalhe a operação de navios nesta rota marítima (incluindo imprevistos causados por greves nos portos, problemas mecânicos, etc), o trânsito de camiões entre as origens ou destinos das cargas com os respetivos portos. O cumprimento do horário é avaliado, tendo em conta as incertezas associadas, bem como os atrasos ocorridos nas entregas, a ocupação de cada entidade (camiões, condutores, etc) e a fiabilidade global do sistema de transporte. Foi também feita uma extensa análise à prestação do sistema em termos económicos. A partir de todos os indicadores medidos ao longo do serviço foram retiradas conclusões que apontam para o método mais vantajoso em termos globais. Nas condições consideradas, tentado reproduzir ao máximo a realidade das tipologias de transporte abordadas dentro da Europa, o transporte intermodal revelou-se economicamente consideravelmente mais vantajoso face ao unimodal. Em condições de transporte equivalentes entre as duas modalidades e para os mesmos níveis de fiabilidade, a solução intermodal traduziu um custo global inferior à unimodal em 30%.

Palavras-chave:

Intermodal, Modelação de cadeias de abastecimento, Simulação de eventos discretos, Transporte marítimo de custa distância, Fiabilidade.

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ACRONYMS:

Ro-Ro: Roll on, Roll off ships

SSS: Short Sea Shipping

TEU: Twenty-foot equivalent Transport Unit

GHG: Green House Gas

CO_2: Carbon Dioxide

NECTAR: Network on European Communication and Transport Activities Research

ICT: Information and Communication Technologies

KPI: Key Performance Indicators

1. INTRODUCTION

1.1 Background and motivation

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, as published by European Commission (2019), 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%.

The CO_2 emissions from freight transport have been increasing in the last decades. Eurostat (2017) declares that in 2015 CO_2 emissions represented 33.8% of the total EU emissions[1] 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 "m*ovement 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 and Demir et al. (2016) state that 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 partis 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.

[1] Excluding international maritime (international traffic departing from the EU) and including international aviation.

To comply with these circumstances that add cost an uncertainty to road freight transport, the study presented in this thesis 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 fulfil 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 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, according to 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 – configurations. 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. Banks (1998) distinguishes two groups of simulations, discrete and continuous, 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[2].
- 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.

1.2 Objectives

- 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.

1.3 Structure of the thesis

The thesis is organized in seven chapters and respective appendices. Chapter 1 is the introduction of the topic to be discussed the related background and including the goals and structure of the work.

Chapter 2 contains the literature review of the works of up until today, as well as the adopted theories from the information gathered

In chapter 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.

Chapter 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, being followed by three subsystems recreated in ARENA. To end this chapter, model verification, validation and evaluation is approached.

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[2] "A bottleneck is a point of congestion in a production system that occurs when workloads arrive too quickly for the production process to handle. " via web: https://www.investopedia.com/terms/b/bottleneck.asp

Chapter number 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).

Chapter 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 chapter, number seven, contains the main conclusions taken from the work produced, along with some recommendations and suggestions for future work to be developed.

2. LITERATURE REVIEW

2.1 Intermodal freight transportation

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

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, Erfurth and Bendul (2017) claim that the impact of long-haul transportation as distinctive element of intermodal chains is under researched.

Macharis and Bontekoning (2004) and Caris et al. (2008) reviewed the most relevant scientific publications disseminated so far, regarding intermodal transport operations. Both demonstrated that intermodal freight transportation research was emerging as new and dynamic transportation research application field. It was gaining a large variety of intermodal researchers, a large variety in research specialties as well as a range of intermodal characteristics that justify an intermodal research agenda. Although, they conclude that most studies focus on the strategic level, related to infrastructure network design and terminal allocation. They found that there are not many studies where decision makers are taken into account in spite of the necessity of a high level of coordination to improve the performance of intermodal freight transport. Jensen (2008) also is convinced that intermodal transportation is a young area of research with a lot to explore and stands out the constant presence of competitiveness, and so its aspects were of prime concern. Concepts such as sustainable competitive advantage (SSCA) and market entry ability (MEA) were approached within the chapter presented.

Nuzzolo et al. (2013) realized that despite the wide number of studies concerning simulation of freight transport, it was widely agreed that the proposed approaches so far had not yet been fully validated and frequently had not provided the expected results. The main reason for that is the lack of data in detail for modelling so the output results can be realistic, and it is at the urban level that this deficiency is more pervasive.

In between 1993 and 2013, only few transport forecast models were able to deal with large-scale problems while having into consideration the micro-mechanisms in the underlying demand (decision making processes). The supply of services involves several decision-makers responsible for production quantities, distribution of goods and marketing strategies. The authors identified several points to improve, such as: The need to engage governments in coordinating, collecting and sharing and consistent and extensive freight dataset; Interactions between decision-makers should be studied more deeply, as well as the external influences on freight system agents (market structure, government policy, traffic management, etc); Simulation models should be oriented to policy-maker needs, in short-distance cases, in order to make correct estimations of the impact due to the implementation of new city logistics measures.

Steadieseifi et al. (2014) discussed the different terminologies used in practice, namely: multimodality, intermodality, co-modality and synchromodality and verified that the latter one did not have much attention from the research community, although it seems very appealing for the flexibility and efficiency it envisions.

From an operational research and revenue-maximizing perspectives, Tawfik and Limbourg (2018) reviewed the state of research in intermodal pricing as an element of vital link to energy consumption and sustainability assessment. The authors identify pricing as a powerful instrument to increase intermodality's share, attain more balanced modal splits and thus reduce environmental impacts. One of the problems detected is the serious deficiency in attaining high load factors which makes the freight transport systems less sustainable and energy-efficient. Another deficiency identified is that shipper's behavior likeness at the lower level (fright mode choice and traffic network assignment) are not well integrated in virtual networks. Since interaction between the different modes, as well as the potential generation of economies of scale with higher payloads reflect in marginal cost decrease, it is suggested that research extensions for the problem deserve in-depth consideration.

Macharis and Geurs (2019) reviewed the European communication and transport and present a research agenda along eight topics of the Network on European Communication and Transport Activities Research (NECTAR). The authors start by standing out the growing complexity and need for multi- and interdisciplinary transportation research. Then, the sustainability needs to be addressed as soon as possible, not forgetting the policy-making involved in between. Afterwards, the author approaches the Information and Communication Technologies (ICT) and digitalization, the emerging operational and business models for transportation and logistics and its profound impacts on economies and societies.

2.2 Economic efficiency of intermodal networks

Having the intermodal freight transport networks economic efficiency related with total cost reduction as main goal, the following case studies were developed and here summarized. The main concern was, in all, to improve the economic efficiency of the transport, intending to use intermodal transport solutions to replace less sophisticated ones.

Jensen (1990) developed a heuristic model that attempted to determine the most efficient operating procedure of an intermodal transport system. The model shows that transportation costs decrease by transferring goods from the unimodal transportation system to the intermodal one, in this case road/rail, to deliver them door-to-door. It also shows an increase on the flow traffic around the terminals.

Based on Jensen model, Flodén (2007) developed the Heuristics Intermodal Transport Model (HIT-Model) for decision support concerning combined transport in Sweden. It was gathered information about costs, external impacts, and overall performance on intermodal transport systems. For the model implementation it was considered the quantity of goods transported, transport routes and connections and the rail transport means used within the route. The HIT-model has shown that there is a great potential for combined transport in Sweden. Both business economic costs and environmental effects can be lowered via combined transport. It is also seen that in terms of economic competitiveness intermodal transport is mostly better, especially with more relaxed delivery/pick-up times.

Southworth and Peterson (2000) dedicated themselves to the routing simulation of tens of thousands of intermodal freight movements in the USA reported in the 1997 United States Commodity Flow Survey, involving combinations of rail, truck and water transportation. A geographic information system (GIS) software was of utmost importance to accomplish the task, although it is expected to exist several post-model adjustments needed, since there was not a nationally representative sample of how either trucks or intermodal shipments move around the USA and thus some parameters may not be well calibrated.

Groothedde et al. (2005) by presenting the results of the design and implementation a collaborative hub network in a Dutch important node in the worldwide logistics, discussed the relevance of collaborative intermodal hub networks, which promote economies of scale and scope in logistics networks. As consequence, the main priority is not to find the best transport mode but to find the best combination of modes. Although, intermodal transport was not seen by the authors as solution for every shipment, but a necessary alternative in order to synchronize shipping between expensive but fast, responsive and flexible means of transport (full-road) and inexpensive but slow and inflexible means (intermodal).

Janic (2007) developed a model for calculation the internal and external costs of a given intermodal rail-truck and equivalent road freight transport networks in Europe. The results showed that both network costs decrease as door-to-door distance increases (economies of distance); for intermodal transport networks, the average full costs decrease at a decreasing rate with the quantity of loads rises (economies of scale) while in full-road transport networks full costs are constant.

Trant and Riordan (2009) studied the technical and economic feasibility of intermodal transport solutions across specific corridors between Ireland and Continental Europe and Sambracos and Maniati (2012) within Greece. 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.

Stingă (2017) developed a routine for a unimodal maritime transport network which main goal is to minimize the unitary cost, taking as variables the type of goods transported, the type of ship used and the loading/unloading time and costs at the ports. The authors used the Bellman Kalaba's algorithm, filling a matrix with the direct distances between modes in order to find the optimal route.

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. This network serves both domestic and international trade. The present research determines the transhipment target up to 2030 and evaluates the creation of 2 or 3 large terminals that boast the quality of service and plenty of transhipment points. Also by investing in the railway infrastructure, the speed of commerce will increase as well as the amount of cargo transported, allowing the development of economies of scale in terminal-to-terminal corridors. The development of the intermodal network is most expected to also reduce traffic, environmental impacts between other measurable social benefits. It is to point out that the proposed model considers minimal expenses and emphasizes the presumed better utilization of existing infrastructure.

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.

In Wiśnicki and Milewski (2018) research is presented on the analysis of the impact of the integration of intermodal chains on logistics costs and thus on global trade, emphasizing specially the problem of the diversity of standards of containers and transport technologies around the world. Different configurations were simulated and the total costs of each chain were calculated as well. The authors compared the intermodal chains between the USA and Europe and concluded that the use of 53' or 45' containers alternatively to standard 40' in door-to-door transport, could lower the cost of trade between them. Since it is observed that the amount of light and very light commodities transported in containers are increasing, the tendency is to make use of larger containers. However, it is clear this would imply significant changes in both maritime section and land infrastructure.

The role that efficient roll-on/roll-off port terminals play in providing cost and time efficient cargo handling operations in these fundamental intermodal nodes of supply chains has been studied by Santos et al. (2018). These authors presented a case study dedicated to the operation of a shortsea Ro-Ro terminal in the port of Leixões, in Northern Portugal, providing statistical data valuable for modelling Ro-Ro terminal operations.

Ypsilantis and Zuidwijk (2019) based on a real case in The Netherlands, developed a Mixed Integer Linear Program (MILP) for a vehicle routing problem in a port-hinterland network that connects a set of near seaport container terminals with near dry port terminals. The impact of cooperation through capacity sharing between close dry port terminals and the trade-offs in the optimal barge network design were analyzed. Many parameters were varied, such as the demand volume, expected delays and minimum service requirements. Depending on the parameters set of each configuration, the cost reductions vary from 12% to 48%. With higher cooperation it was considered bigger barges too, allow to serve more Origin-Destination pairs in a round trip. Bigger barges help to reap economies of scale and the small barges to operate at a higher frequency. Routes with many stops help to consolidate the demand providing high frequency of services were also compared with others with few stops that have shorter circulation times.

Tawfik and Limbourg (2019) studied the freight transport for the Belgium domestic freight transportation and long-corridor cases, based on Nomenclature of Territorial Units for Statistics (NUTS) data. For Belgium domestic transport, the low share of intermodal transportation observed was already expected since there are higher costs for intermodal transport comparing with the all-road equivalent because the breakeven distance for intermodality's favor is hardly reached for the considered distances of less than 400km. Although, within intermodal transport, IWW are favored over rail transport probably due to rail high fixed costs. Thus, since IWW are limited, it is seen as necessary to subsidize rail transport, at least to leverage it in its early stages. Al last, from an environmental perspective, modal shift is identified a solution that minimizes emissions.

2.3 Emissions from intermodal transportation

In another side, one other big advantage of intermodal freight transport is emission reduction potential. The following studies approaches the green aspect of freight transport as main subject under analysis.

Jemai et al. (2012) approach the subject of green logistics by finding routes for vehicles to serve a number of customers, which main goals are to minimize the total traveled distance and CO_2 emissions. To solve the problem benchmarks and perform statistical analysis it was applied the NSGA-II algorithm (Non-dominated Sorting Genetic Algorithm II). The results obtained show that minimal distance does not imply minimal emissions, but the results show and prove the effectiveness on emissions minimization.

Roso et al. (2009) approach the dry port concept, taking a logistics, economic, technological and environmental perspectives and state that it goes beyond connecting a seaport with its hinterland. Apart from the ecological benefits, by shifting flow from road to rail the general quality of life increases with the external costs minimization. This way, seaports can also secure the market by increasing the throughput without expanding themselves and provide better services to transport operators and shippers. Still within the dry port concept, Hanaoka and Regmi (2011) reviewed the status of intermodal freight transport in Asia from an environmental perspective, focusing the importance of the development of dry ports in hinterland locations. It is concluded demonstrated by several case studies that railway connections to dry ports reduce CO_2 freight emissions and reduces the number of long-haul trucks through modal shift. The improvement of operational efficiency, the modernization of infrastructure and the use of greener power sources are of utmost importance for the implementation of such changes in Asia freight transport.

Demir et al. (2016) developed a novel continuous-time mixed-integer programming formulation which integrates available transportation options in a sustainable way. The case study considers road, rail and inland waterway transportation modes, along the Danube region between Hungary and Germany which serves both as origins and destination of containerized goods. Since the travel times is taken as an uncertainty, a large set of configurations were evaluated in order to develop more robust transportation plans in terms of costs, time or environmental impacts. It was obtained interesting results and depending on the configurations (and objectives set) the total costs, travel times and environmental effects change, but the focus is on the balance between costs and environmental effects minimization. At last, the results obtained by the proposed stochastic mathematical formulation were compared with the ones obtained on a real-life case study and it is verified that the solutions generated are robust.

2.4 Intermodal transport planning and development

In terms of other innovative studies concerning the improvement of intermodal freight transport chains, not having the total freight transport cost as main parameter under analysis, there are the following.

Li et al. (2015) approach intermodal freight transport planning problems between deep-sea terminals and inland terminals in hinterland transport at the tactical container flow level. The authors developed an Intermodal Transport Freight Network (ITFN) model to capture characteristics like time schedules of trains and barges, time-dependent transport times on freeways and also the physical limitations of the network. The behavior of transport demands is dynamic and traffic conditions change continuously during the entire freight delivery process. It includes unexpected transport order requests, transport order cancelation, the dynamic evolution of transport times on freeway links, among others. With this simulation it is possible to detect the limitations of the network and calculate the total delivery cost in the simulation study, being the prediction horizon of the transport demand and traffic conditions the key factors for the accuracy of the outputs obtained.

Mattei et al. (2015) describe an innovative Geographic Information System (GIS)-based model for analyzing different policy measures and intermodal configurations. For that, it is provided a wide set of parameters dealing with policies, rail and road infrastructures, transportation units, vehicles and loading systems. The model allows the user to identify the value-added activities and reduce the inefficiencies, analyze the impact of every activity on the total transport lead time and to quantify the impact of potential new actions, technological innovations, and infrastructure improvements. As foreseen by Flodén (2007), the authors point out the future continuous development of these GIS-based decision support systems as one useful tool to support the emerging transport systems concepts such as Intelligent Traffic System (ITS), in which the real-time data collection and analysis plays a critical role to study and improve the traffic state.

An aspect that did not have been much a subject under analysis by the research community is the effect of long-haul transportation on the performance of an intermodal transport chain in terms of transportation time and transportation time reliability. Erfurth and Bendul (2017) contributed to minimize that gap in the literature by first, contemplating transportation time and its reliability in the performance metrics and considering them as decision variables, and secondly, by sketching the influence of long-haul transportation on them. The results obtained from the proposed simulation model show that the major impact on transport time reliability results from different distributions involved in the individual transport legs: pre-, long- and post-haul.

Also, 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. To do so, it was applied a combination of algorithms that measure the mean standard deviation of the transport times, therefore the transport time reliability of an intermodal transport chain could be estimated.

2.5 Simulation of intermodal transportation

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. Preusser (2008) studied in her PhD thesis a combined simulation and optimization approach to improve the supply chain by simultaneously optimizing a large number of possible transportation decisions. By integrating dynamism and uncertainty, it allows to model and solve more realistic problems. The simulation model was applied successfully to several test examples and has delivered competitive results much faster compared to conventional mixed-integer models in a stochastic environment.

In another study, Song et al. (2013) proposed a simulation-based approach for sustainable transportation optimization by seeking an optimal combination of transportation planning and operations strategies that minimize generalized costs of multimodal traveling.

To make transport plans more reliable and avoid late deliveries, Hrušovský et al. (2016) proposed a hybrid simulation (using the Anylogic University 7.2.0 software) and optimization approach to investigate the intermodal transportation planning problem in a stochastic and dynamic environment. It was also taken into consideration greener transportation solutions for the problem under investigation. The methodology was validated on a real-life case study, which proved the reliability of the generated solutions.

In order to take better advantage of an existing intermodal freight system, Kelle and Jin (2016) built a system-level intermodal simulation model for Louisiana that includes highways, railways, and waterways and also integrates the connections between the different nodes. The authors developed a simulation framework based on ARENA simulation software, developed the simulation model and calculated parameters such as mobility, reliability safety and environmental performance for the existing intermodal freight system of Louisiana. The model was then validated with the traffic counters on certain locations from various databases. At last, three different configurations were analyzed so the main what-if questions could be answered.

Regarding agent-based simulation models:

Reis and Macário (2008) studied the process of replacement the road service by an intermodal rail-road service due to a change in strategy of a Portuguese shipping company. To do so, the author built two simulation models for both transport system solutions, using the agent-based software: AnyLogic 6.0 Educational Version. The models were then evaluated using four factors: out of pocket cost of transport, plus three quality factors (transit time, flexibility, and reliability). One main requirement was to no change the out-of-pocket costs and considering all the particularities of this case study, the authors concluded that intermodal transportation would become disadvantageous.

Reis (2014) presents an agent-based simulation model (developed using ANYLOGIC Version 6.4.0

Software) to check if mode choice variables - price, transit time, reliability, and flexibility - used in medium to long-distance transport services can be used to explain the behavior of agents in short-distance transport cases. A case study of a short distance intermodal transport service was used to test this hypothesis. The competitiveness of the intermodal transport services was compared against a hypothetical road transport service. Competitiveness was assessed by measuring the performance of each transport option in relation to the abovementioned four mode choice variables in different demand configurations. The simulation results a clear advantage for road transport for short-distance transport cases, except for the price variable in few configurations where intermodal outperforms road transport. All other mode choice variables point out intermodal as disadvantageous.

3. DESCRIPTION OF THE TRANSPORTATION PROBLEM

In the simulation model presented, it is considered typical transport operations of a logistics company that need to send general cargo from Northern Portugal to Northern France, Belgium and Luxemburg in a containerized form. To facilitate, the destination countries/cities, will be mentioned simply as *Northern France*. The cargo units considered are equivalent to a full truck load or 40 feet container.

The logistics company operates two fleets of trucks, one in Portugal and another in Northern France. The truck drivers are of two different categories: the ones who only operate in Portugal or France and the ones who cross borders to take the cargo by road from origin to destination (unimodal transportation). Regardless of the category, all drivers must comply with the driving time legal restrictions to the EU regulations, taking the mandatory daily and weekly rests[3] of at least 11 hours and 45 hours, respectively. These rules are published in European Parliament and Council (2006).

The number of drivers and trucks in each location is fixed and its assignment to service is dependent on the availability of both simultaneously.

When cargo is ready to ship in each origin, it has already a delivery date and a destination attributed. The booking is made and the logistics company estimates how long each solution unimodal or intermodal – would take to get the cargo in the respective destinations. This estimation is done resorting to average velocities and in the Ro-Ro vessel schedule, since it is known the size of each leg. Given the many advantages found in the literature, it is set a preference for the intermodal transport solution, forwarding by fully road-based transport only the cargoes that are expected to be delivered outside time window via intermodal transportation.

It is noteworthy that the ship generally takes much longer than the truck, beyond the fact that it has a weekly schedule. This makes that cargoes cannot be shipped independently, having to be gathered progressively and then loaded in the Ro-Ro vessel. Through fully road-based service, all cargo units are independent from each other, relying only on the availability of trucks and drivers. Although, as concluded in many studies mentioned in the previous chapter, intermodal freight transport brings several economic, environmental, and societal advantages thus it is favoured over the unimodal solution.

There are six origins where cargo units are generated and six possible destinations for each one. All origins and destinations are cities at known distances from each port. Yearly, it was set a (fixed) total number of cargo units to be generated and the pairs origin-destination are fixed.

The occurrence of bookings throughout each month is, however, uncertain. The demand for freight transport increases worldwide in Autumn, mostly because of Christmas in December. Hence, the system will generate more cargo in those three Autumn months to cause the demand increase.

[3] 'rest' means any uninterrupted period during which a driver may freely dispose of his time.

Cargoes have a time window for delivery without penalties and to every unit generated, it is randomly assigned a delivery date. Based on it, the system chooses the shipping solution. In other words, cargoes can be delivered from the delivery date on (never before), until the end of the delivery time window.

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.

The fact that cargoes are shipped separately brings a level of independence that cannot be found in other transport types, like maritime or rail transports. If in the middle of a voyage there is a problem with the truck and it gets suddenly out of service, it is easily replaced by another one so the voyage continues and the cargo gets to destination with just a little delay.

This independence brings also the readiness do start the voyage right after a booking is made, which reduces the dwell 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 24 hours, 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.

There are not being considered truck mechanical failures since it is done periodic maintenance frequently and in practice, when a truck has a failure it is quite easy and quick to replace the truck for another, implying on it a not significative delay.

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 with road transport, as a way of minoring the road infra structures saturation. It is also taken as fundamental for the sustainable development of the European Union. Nevertheless, it is not intended to create a dispute between the different transport modes, but to foment the cooperation between them, leading to a competition indeed but inside multimodal transport chains.

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.

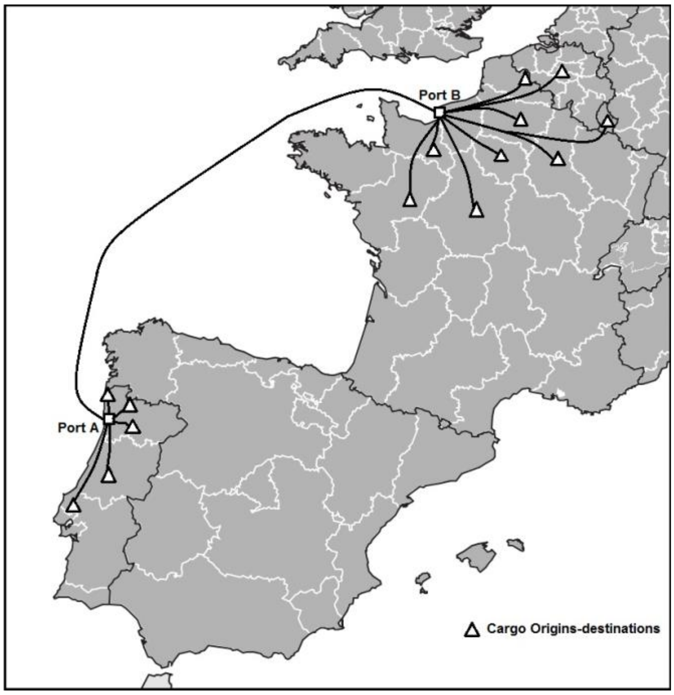


Figure 1 - Definition of the many-to-many transport problem.

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 loading process is carried out using the terminal's own fleet of tugmasters which tow the wheeled platforms (mafis) with the stacked containers or the semi-trailers into the ship's cargo spaces. 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 Winter time, 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) are measurable values that indicate how effectively the system is achieving key business goals. The KPI defined are intended to express the desired outcome fulfilment 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 entities 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 of 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 TRANSPORTATION 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.

The simulation does not optimize the system, it tests the performance for each set of given input parameters. By changing inputs, the system behaves differently having different performances. Later, in chapter 6, it will be exposed the different configurations analyzed for each set of input parameters and how the performance indicators change.

There are two groups of simulations, discrete and continuous [Banks (1998)]. The first one is the most frequent, focused on the entities (i.e. truck driver) and time advance stepwise between the different events that creates a change in an entity. The second one, continuous simulation, has a continuous running clock and simulates every instant, even if no activity occurs. The choice of simulation type depends on what is being modelled in the system [Banks et al. (2009)]. The transport system under study fits well with a discrete system since entities change state at distinct moments in time (uncertainties).

4.1 Discrete event simulation software: ARENA

The software Arena Simulation Software (version 14.0) is developed by Rockwell Automation company. This simulation modelling software provides all functions required to fulfil the task. Its interface is quite user-friendly for model development, it has animation facilities and tool to generate the detailed statistical reports.

4.1.1 Elements of the simulation model

Entities are the assets that move around the simulation, change status, affect and are affected by other entities and the state of the system. They also affect the output performance measures by their performance/efficiency in the system. Generally, entities are created, move around awhile and are disposed afterwards when their work in the system is finished. An example of that are the cargoes that are generated randomly and when delivered in destination, they are disposed.

There are also the cases when entities never leave the system and keep circulating in the system, like drivers or trucks, that work in cycles. However, all entities have to be generated and this type of entities often are created in the beginning of the simulation, as if they were already part of the system design.

Some entities are created just to affect the system, like when an event that compromises the service is initiated (as a strike in a port), and for this an generic entity is created just to affect the system and immediately after, it is disposed.

- **Entities** examples:
    - Cargo units

  - Drivers
  - Trucks
  - Others

Attributes are used as a way of individualizing entities. They are a common characteristic of every entity, having a specific value that may differ from one entity to another. For example, to all cargoes it is assigned a destination but the destination changes continually, thus, the value of that attribute changes within a group of cargo units.

Attributes are tied to specific entities and does not change with time unless they pass by a specific module – ASSIGN module – programmed to do so.

- **Attributes** examples:
  - Cargo origin
  - Cargo destination
  - Instant of cargo generation in system
  - Driver number
  - Travel velocity

Variables can be of two types: User-defined or ARENA built-in variables. The firs type work as attributes, not for a specific entity but for the system. In other words, variables are not tied to specific entities, but rather belong to the system at large. It has the same value to all kinds of entities, and therefore they are called "global" or "system" variables. It can exist many different variables in the model, but each one is unique.

The ARENA built-in variables are variables that the software has in its design and constantly updated, but the user can make use of them when needed. For example: time of simulation, number of busy resources, etc.

- (Global) **Variables** examples:
  - Bad Weather on/off
  - Bad Weather event counter
  - Delivery window (ex. 48 hours)

Entities seize (units of) **resources** when available and releases it/them when finished. A resource is given to an entity, not the reverse, and an entity can make use of more than one resource at the same time. For example, for a truck to deliver cargo in the port, the truck needs to seize the resource *port* and if the port is closed, the truck has to wait until the resource is available (until the port opens). Resources can have schedules for availability and can change in number over time.

- **Resources** examples:

- Port (open)
- Intermodal Portuguese truck driver
- Truck (France based)
- Truck (Portugal based)

Queues, as its own name point out, are places where entities wait when they cannot proceed its way, for many possible reasons. For example, when an entity needs to seize a resource and there is none available, when trucks and drivers are waiting to be summoned to pick a cargo that had been generated in system, when it occurs that roads are blocked due to bad weather and the batch *truck-driver-cargo* waits until the bad weather event is finished, etc.

- **Queues** examples:
    - Cargo in port
    - Truck park
    - Drivers available

4.1.2 Simulation software modules

It has been used blocks for modelling which are connected between each other in accordance with dependences as well as operations in the studied system. The Arena building blocks are divided into several categories, but the ones found appropriate for this type of system could be all found in the *Basic Process* and *Advanced Process* panels

In the Basic Process panel, it can be found the flowchart and data modules that will be used to model the processes, such as: CREATE, DISPOSE, PROCESS, DECIDE, BATCH, SEPARATE and ASSIGN.

The CREATE modules generate entities, such as cargo units, drivers, etc. The time between each generation is given by the uniform distributions for each month of the year, as shown in Figure 2. The DISPOSE module is to remove from the system entities which activity is concluded, like a cargo that reached destination.

The PROCESS module is used to allocate resources, holding or not the entities involved too for time necessary to perform the respective activity. For example, to seize a truck one unit of the resource *Truck* must be available and it is kept “busy” until the truck comes back again to truck park.

The DECIDE module determines where to forward the entity based on one or more conditions. For example, if the truck travelled 5000 km or more it is routed to a HOLD block to simulate the time spent in cleaning and maintenance.

The BATCH and SEPARATE modules are used to merge entities or separate them, respectively, as when a driver starts a voyage it is merged with the truck.

The ASSIGN module is used to assign new values to variables or attributes or other system variables.

In Figure 2 are shown the modules used and described previously, from the Basic Process category.

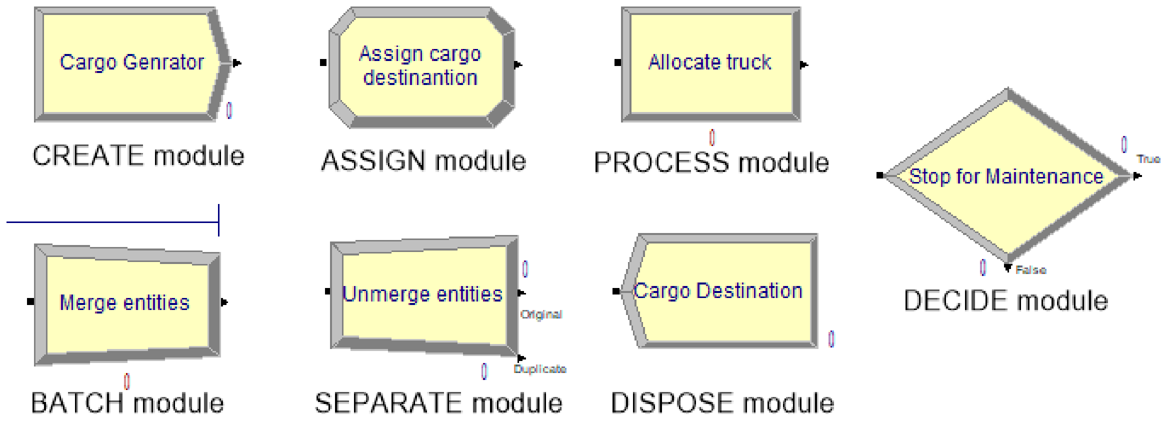


Figure 2 - Basic Process modules in ARENA simulation model.

In the Advanced Process panel, it can be found additional functionality for modeling the process, such as: DELAY, HOLD, MATCH, READWRITE, SEIZE, RELEASE, REMOVE, SEARCH and SIGNAL

DELAY is used to hold an entity in this module for a specified amount of time.

HOLD is used to hold an entity based on a condition or until a signal is sent by the SIGNAL module, as when it is time for departure, a signal is released, the loading operations start and the voyage starts after.

MATCH brings together a specified number of entities waiting in different queues, as when a cargo waits to be picked up by a truck (and driver). When the truck arrives it is put together with a cargo in queue, right before entering the BATCH module to be merged.

READWRITE is used to either read data from an input file the user creates and to assign the data values to the corresponding variables and attributes or to write data to an output file.

SEIZE allocates units of one or more resources to an entity and the RELEASE does the opposite, it frees resources from entities. The modules *Seize*, *Delay* and *Release* are part of the *Process* module and used separately when it is convenient.

REMOVE removes a singles entity from a specified position in a queue and sends it to a designated module. It is used, for example, to “load the ship” by removing cargoes from the semitrailer yard queue.

SEARCH looks up in a queue the rank of a specific entity unit. For example, the multiple cargoes ready to be picked up at origin are put in the same queue (to reduce the number of simulation modules) but when a truck and driver are requested it is specified the cargo to be picked up and the *Search* modules it used to find it in the cargo queue.

SIGNAL sends a signal value to each *Hold* module that is set to hold an entity until a specific signal is emitted.

In the figure below it is presented an example of each module described above.

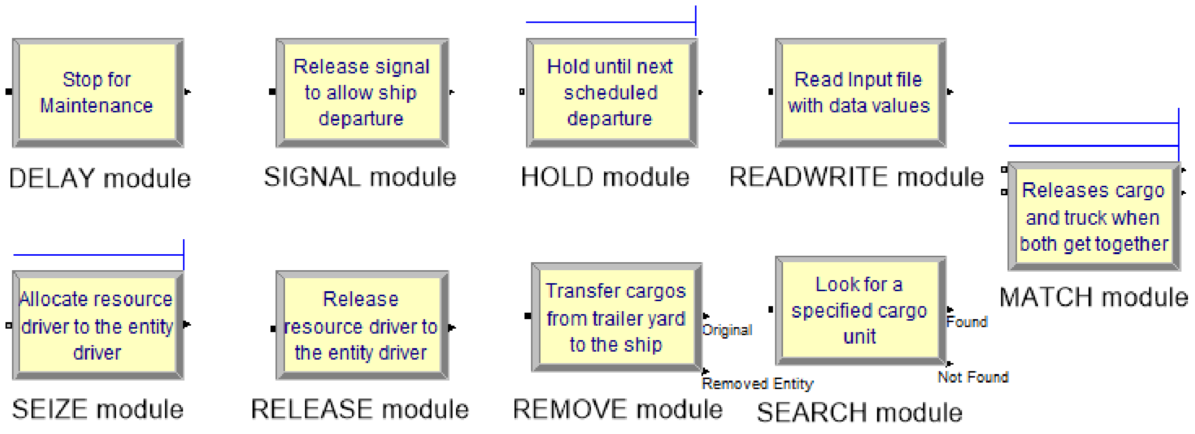


Figure 3 - Advanced Process modules in ARENA simulation model.

4.2 Implementation of the problem

For the work carried out, as a transport system can be seen as a discrete system, the discrete simulation model type was the selected. Altiok and Melamed (2007) describe the main principles of modelling using this particular software, while Figure 4 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 inputs were combined with the random distributions later specified, such as delays, velocities, system failures, etc. To obtain reliable results it is necessary to bridge the discrepancies that can be caused by outlier values from the random distributions in each run. Thus, the model was re-run several times (replications) until the system and consequently, the output performance indexes, stabilized.

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).

After this, there are three conditions that must be satisfied for a cargo unit to be shipped by intermodal transportation. If one of the first two conditions are not satisfied, the cargo is automatically referred for unimodal transport (road transport only). The conditions are verified by the following order:

1. The estimated delivery date must happen within the delivery time window (delivery date set plus 48h),
2. A cargo unit booked with less than 24h before ship departure has to be accepted. If booked more than one day before ship departure, this condition is ignored. This decision is made following the "Last Minute Cargo" distribution specified in Table 5 (page 42).

3. If it can be predicted that cargo will arrive at the port when it is still closed, the cargo is kept at its origin for the time needed to fulfil this requirement and the truck is called.

If it is only the third one that is not satisfied, the cargo is held until this condition is fulfilled. After that, if the first two are still positive, the system requests a driver and a truck to pick the cargo up at its origin and deliver it to the Port of Leixões.

In case the intermodal solution is selected, the entities *driver* and *cargo* go through *Intermodal Sub-model 1* to the port of Leixões and then through *Intermodal Sub-model 2*, which includes the French port of Le Havre and subsequent on-carriage operations to the final cargo destination, as shown in Figure 4. In case the unimodal solution is choosen, the Unimodal Submodel is used. These submodels will be explained in the next sub-sections.

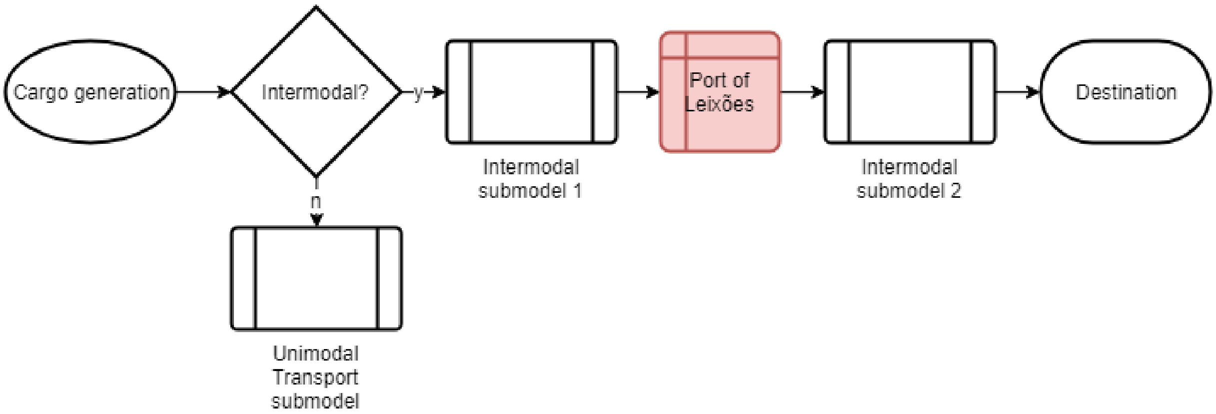


Figure 4 - General layout of the simulation model.

4.2.1 Intermodal service

If the system uses the intermodal solution, the cargo enters *Intermodal Sub-model 1*, which is illustrated in Figure 5. Logically, to pick the cargo up it is necessary a truck and a driver available. The truck speed is assigned and the voyage from the truck fleet park (company facilities) to cargo origin starts. When the truck arrives there, the two entities are merged and the voyage to the port of Leixões starts immediately. Despite the time of arrival at the port is estimated before truck departure, there is a chance that the port is closed and, in that case, the entities wait until the opening. Then, entities are unmerged, cargo is stored in the port, and truck and driver return to the companies' facilities. If it is time to carry out maintenance and cleaning tasks, the truck is held for 24h to do so and the driver is set as available after the eventual daily or weekly rests. The steps described above define the cycle that constitutes submodel 1. When another cargo unit is generated in the system, the same procedure is repeated.

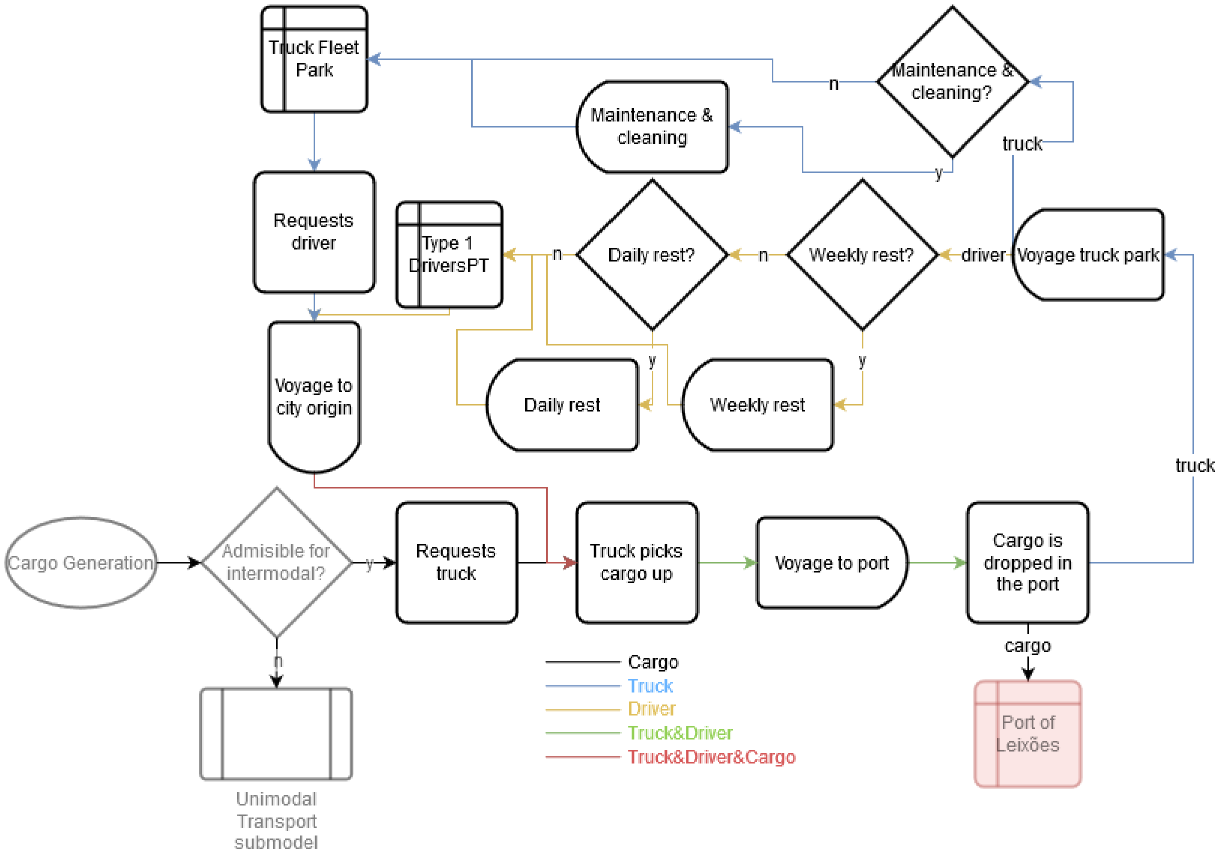


Figure 5 - General layout of Intermodal Sub-model 1.

Intermodal sub-model 1 reaches its end at the port of origin, in Leixões, and there it is initiated the *Intermodal Sub-model 2* right away. This submodule is also represented by a cycle of operations, from Leixões to final destination, as illustrated in Figure 6.

All cargo units in the port are assumed to be ready to be loaded when the ship arrives. As mentioned before, the ship has a fix weekly schedule hence, the arrival in Leixões is set for once every 7 days, at the same day and hour every time. Since one week is expected to be more than enough for the ship each weekly service, it is not considered any chance for late arrivals. There is an uncertainty regarding the time of departure, though, due delays with respect to bureaucracy, temporary unavailability of necessary loading equipment, etc, and several uncertainties that causes delays of another nature, like due to bad weather conditions, technical off-hire, or port strikes. When these events occur, the ship cannot load or leave the port, hence the trip gets delayed, what jeopardizes the transport time reliability. When at the moment of departure, the ship speed is assigned from the respective random distribution, the ship and cargo units are joined together and the voyage starts immediately.

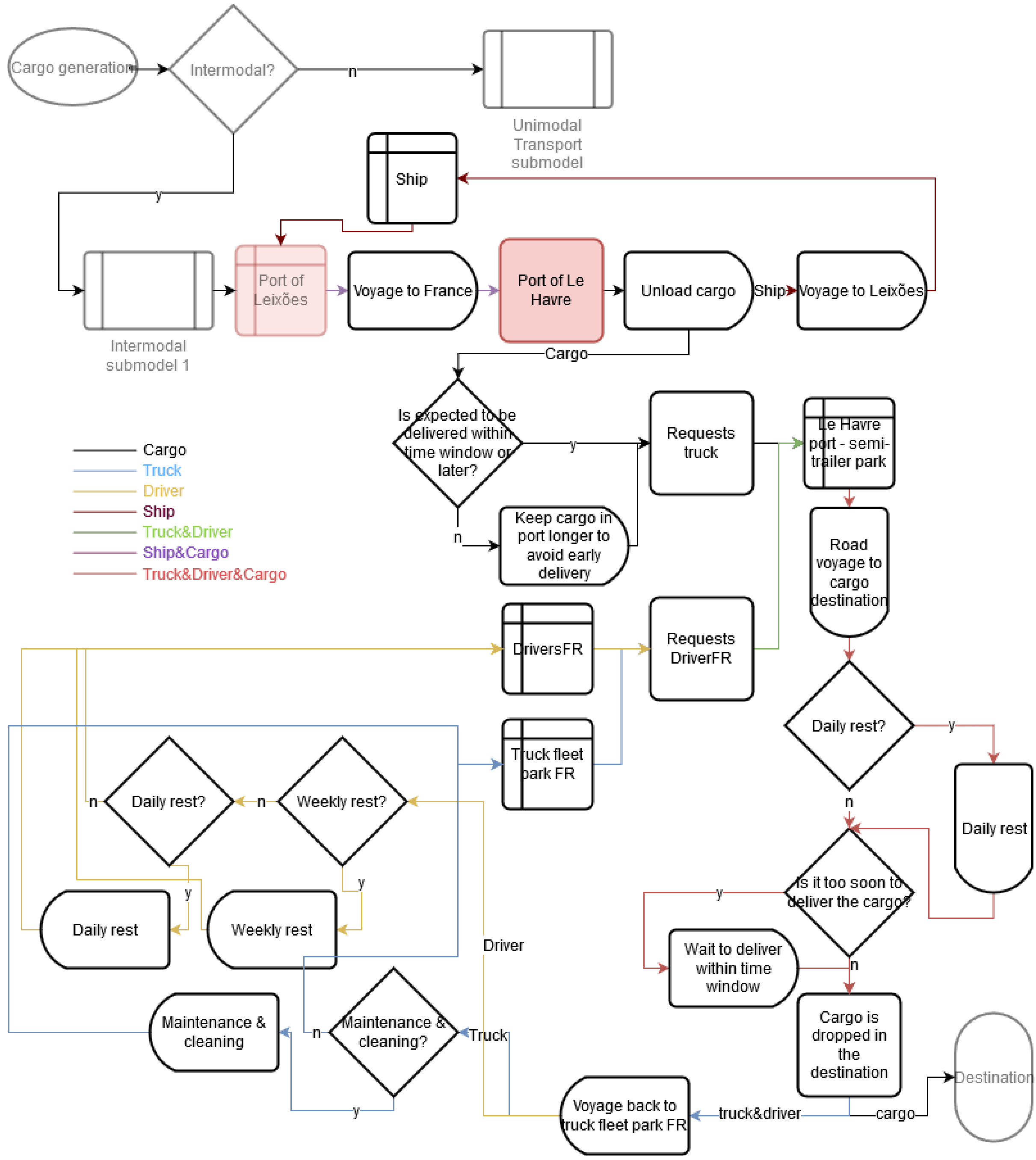


Figure 6 - General layout of the Intermodal Sub-model 2.

The port of Le Havre has the same opening hours as Leixões and undergoes in the same events that compromises the port operation. Due to the long sea leg travelled, it is hard to predict the time of arrival at Le Havre and therefore, there is a chance of the port being closed or out of service. In that case, the ship waits *in queue* to get in the port. After berthing, logistic and bureaucracy procedures have to be carried out and it is assumed to take a minimum of 3 hours. To model the system accordingly, the first cargo is ready for unloading 3 hours after berthing and the remaining units are unloaded at a uniform rate throughout 6 hours, making up a total of 9 hours until all cargo units are unloaded since ship berthing.

The cargo units, randomly unloaded, are stored in the port trailer yard until the trucks come to pick them up. To avoid unnecessary late deliveries, drivers pick first the cargo units which delivery is more urgent, that is, the system estimates the actual time of delivery when the driver arrives and selects for expedition the one that is more urgent in terms of schedule compliance. On the other hand, the time of delivery estimated is also used to allow the system to call a driver/truck and expedite it or hold the cargo in the trailer park longer, since the cargo is not to be delivered before scheduled. When a unit is ready to be shipped and both driver and truck are available, the truck speed is assigned randomly and the voyage starts immediately.

The road distances travelled from Le Havre do destination are much longer than the ones travelled from origin to Leixões what can make necessary for the post-carriage drivers to take daily rests on their way to destination or on their way back to truck fleet park. This may affect the time of deliveries, although it is already taking into account when making estimates of time of delivery.

Analogous to *Sum-model 1*, when the truck and driver return to the company's facilities, the driver is set as available after the eventual daily or weekly rests and the truck goes to truck fleet park immediately, unless it is necessary to undertake maintenance and cleaning works. This cycle ends up and restarts when another cargo unit is ready to be shipped and a truck and a driver are requested.

4.2.2 Unimodal service

When a cargo is generated and the time until delivery assigned is too short and/or the next ship arrival will take too much, there is no possibility of cargo expedition via the intermodal transport while expecting a delivery within the time window. Thus, the unimodal solution brings, despite the intermodal economic, environmental, and societal disadvantages, a major advantage in celerity. Road transport is not dependent from anything else but on the road itself and on the driver and truck availabilities. A cargo unit can be expedited immediately after the booking is made, not having to wait to be aggregated with other units, and this independence has been the key for celerity.

Choosing the unimodal solution, the system enters the *unimodal sub-model*, that is illustrated in Figure 7. 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. This type of drivers differs from the ones considered in the intermodal sub-models since the later only operate on their own country, travelling short(er) distances. The unimodal drivers get subsidies to compensate these and other related inconveniences, which is considered to represent an increase of approximately 20% in terms of salary.

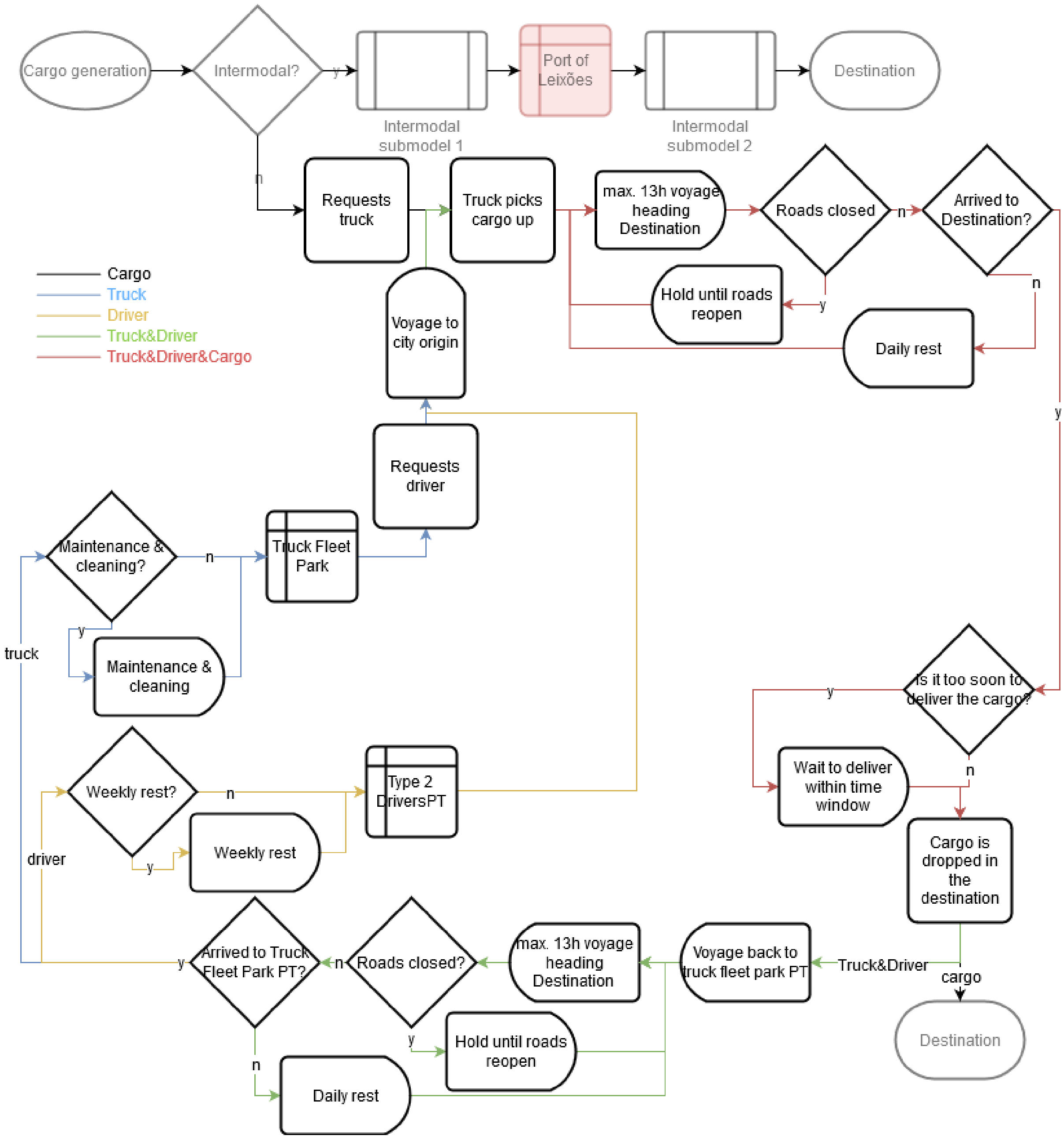


Figure 7 - General layout of Unimodal Sub-model.

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 published in 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.

4.3 Simulation model

The whole system described was then recreated in the commercial software ARENA. The simulation model has 993 modules, what makes it impossible to describe entirely in this dissertation, thus, it will be presented 3 different parts of special interest, containing also the majority of module types used in the whole simulation model.

The first sequence of operations described in detail is the cargo generation (in Portugal) and the following requirement checking in order to choose the transport solution for each cargo generated. Then, a side sub-model that initiates a failure of the system, a bad weather event, is described. At last, the process that recreates the cargo unloading operations in Le Havre is also described.

4.3.1 Cargo generation and separation in queues.

Figure 8 below represents the process of cargo generation and the selection between intermodal or unimodal transport solutions. If all conditions for a cargo to be accepted for intermodal transportation are satisfied, it is conducted through module 13. Otherwise, it will be conducted to module 14 and through module 23.

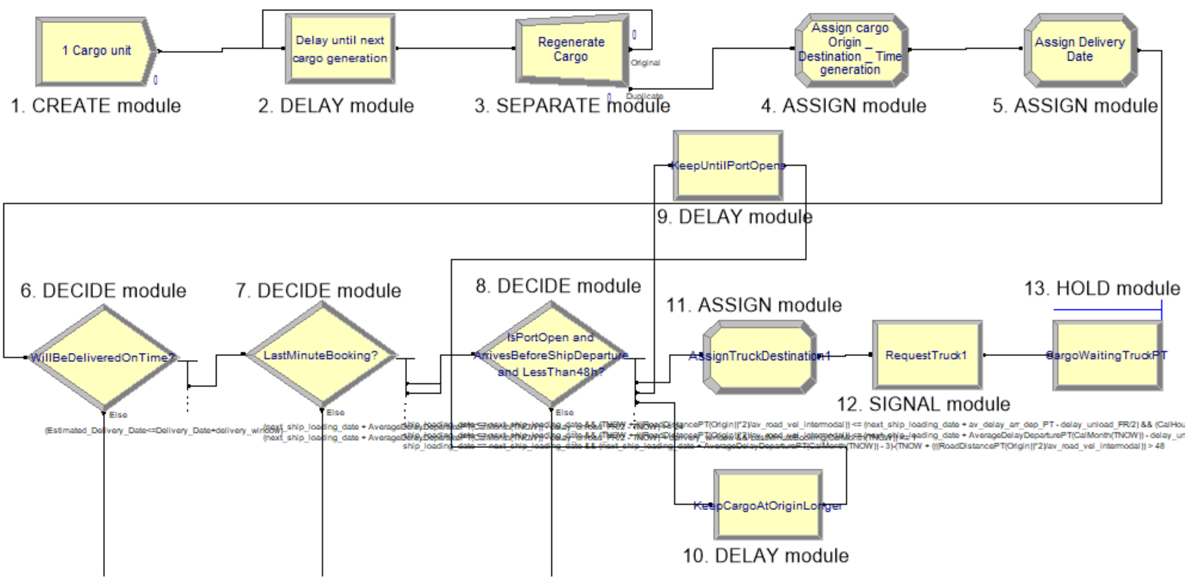


Figure 8 - ARENA submodel for cargo generation and separation in queues (part I).

The explanation of modules 1-13, shown in Figure 8, is as follows:

1. One cargo unit entity is created
2. The cargo reaches module 2 and are retained for a variable amount of time, determined by an expression that manages the cargo generation periodicity in each month of the year.
3. In this module the entity cargo is duplicated, being the original redirected into module 2 and the duplicate into module 4. This is a way of generation more cargo units, alternatively to a CREATE module.
4. Assigns three attributes to the cargo unit: cargo origin, destination, and time stamp.
5. Assigns two attributes: delivery date and estimated delivery date under (normal conditions).
6. If cargo is estimated to be delivered sooner than delivery date assigned in the previous module, the cargo is forwarded to module 7, otherwise cannot be accepted to intermodal and is forwarded to module 14.
7. In this module, if ship departs in less than 24h, the module make use of an expression that sorts the acceptance for intermodal of this “last minute booking”. If ship departure is in more than 24h, nothing changes and cargo goes right to module 8.
8. Three conditions are checked all of them have to be satisfied simultaneously to pass to module 11:
    a. If the truck is expected to deliver cargo at the port within opening hours. If not, cargo enters module 9 and is held until this condition is verified, and re-enters module 8.
    b. If the truck is expected to deliver cargo at the port before ship departure. If not, cargo is automatically directed to module 14 (unimodal transport).
    c. If the truck is expected to deliver cargo at the port after 48h before ship departure. If not, cargo enters module 10 and is held until this condition is verified, and re-enters module 8.
11. Now that the conditions for a cargo unit to be admitted to intermodal transportation were verified, it enters this module and system variables used to indicate to the upcoming truck the cargo origin are updated.
12. Requests a truck to pick up cargo by sending a signal to the HOLD module that represents the truck fleet park and one truck is released to pick the cargo up, as well as an intermodal driver based in Portugal.
13. Cargo is held here until the truck (and driver) arrives to take the cargo to the port by removing it from this module.

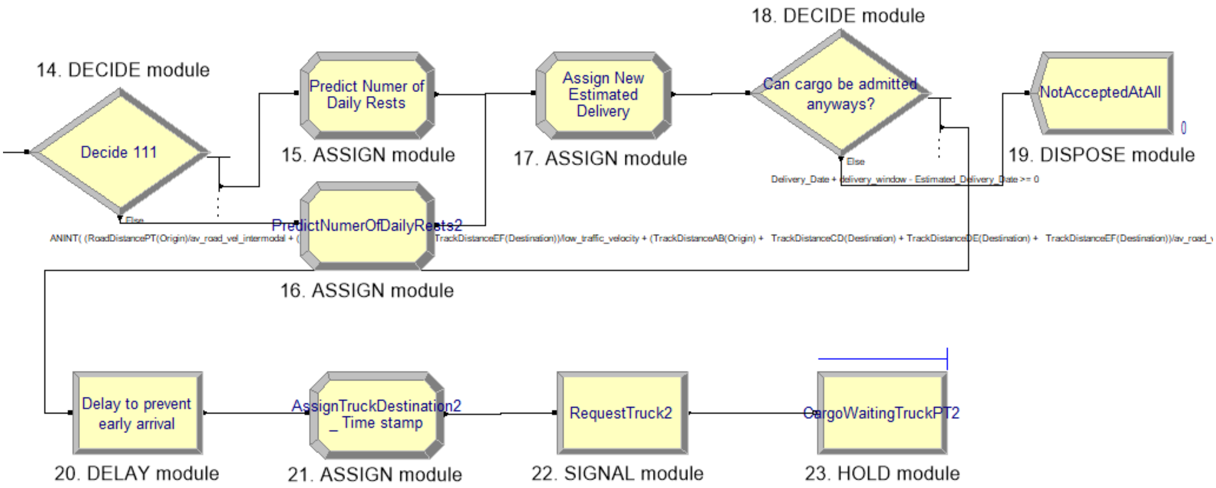


Figure 9 - ARENA submodel for cargo generation and separation in queues (part II).

The explanation of modules 14-23, shown in Figure 9, is as follows:

14. When a cargo unit reaches this module, it means it has been referred to unimodal transportation and so, it has to be predicted the number or daily rests will have to be taken before the cargo is delivered to destination. The number of rests calculated is a decimal and since Arena 14.0 does not round numbers down, a way of predicting the number of daily rests correctly, was through modules 14, 15 and 16.
17. In this module, after predicting the number of daily rests the driver will have to take, the estimated delivery date is updated, considering now the unimodal solution.
18. It is checked if cargo is expected to be delivered within time window. If not, cargo is disposed being redirected to module 19. Otherwise, it is redirected to module 20.
20. To avoid early arrivals at destination, the cargo is held in this module until it is expected to deliver cargo within time window.
21. Similarly to module 11, system variables used to indicate to the upcoming truck the cargo origin are updated.
22. Similarly to module 12, it is requested a truck to pick up cargo by sending a signal to the HOLD module that represents the truck fleet park and one truck is released to pick the cargo up, as well as a unimodal driver (long-distance driver).
23. Similarly to module 13, cargo is held here until the truck (and driver) arrive to take the cargo to the destination by removing it from this module.

4.3.2 Bad weather failure

Figure 10 shows the process of generation of the bad weather events.

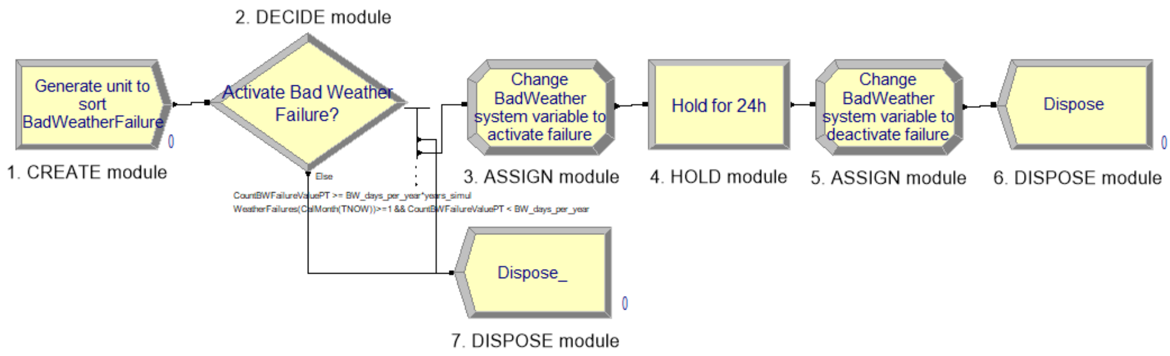


Figure 10 - ARENA submodel to generate bad weather events.

The explanation of modules 1-7, shown in Figure 10, is as follows:

1. Generates entities every 14 days.
2. Every time an entity is created, this module checks if which month of the year the system is and if the limit of bad weather events (two events) has been reached. When in between April and October or when it has been totalized the limit number of events, the entity is disposed through module 7. Otherwise, it is directed to module 3.
3. In this module, the system variable that activates the bad weather events *BWFailureValuePT* is sorted between 0 and 1, resorting to an expression that considers the chances to occur the event in each month. When the *BWFailureValuePT* is equal to 1, a bad weather event occurs.
4. Here, the entity is held for 24h.
5. Resets the *BWFailureValuePT* value to 0, regardless of the value assigned in module 3, and the counter of bad weather events is updated.
6. The entity is disposed.

In module 1, one entity is created once every 14 days in order to create a total of 10 units during the 5 months of autumn/winter, since the chances are percentages multiple of 10. If the creation periodicity was shorter, the bad weather events would happen sooner than later, concentrating these events in the first months of bad weather.

In module 3, if the *BWFailureValuePT* variable value is changed to 1, one bad weather event starts, activating the corresponding HOLD modules spread in the simulation to interrupt the flow of entities, delaying the deliveries. After module 4 is passed, this variable is reset and the system returns to run normally.

4.3.3 Unload cargo in Le Havre.

Figure 11 shows the process of unloading cargoes from ship and the steps followed before calling in the trucks and respective drivers to take them to destination.

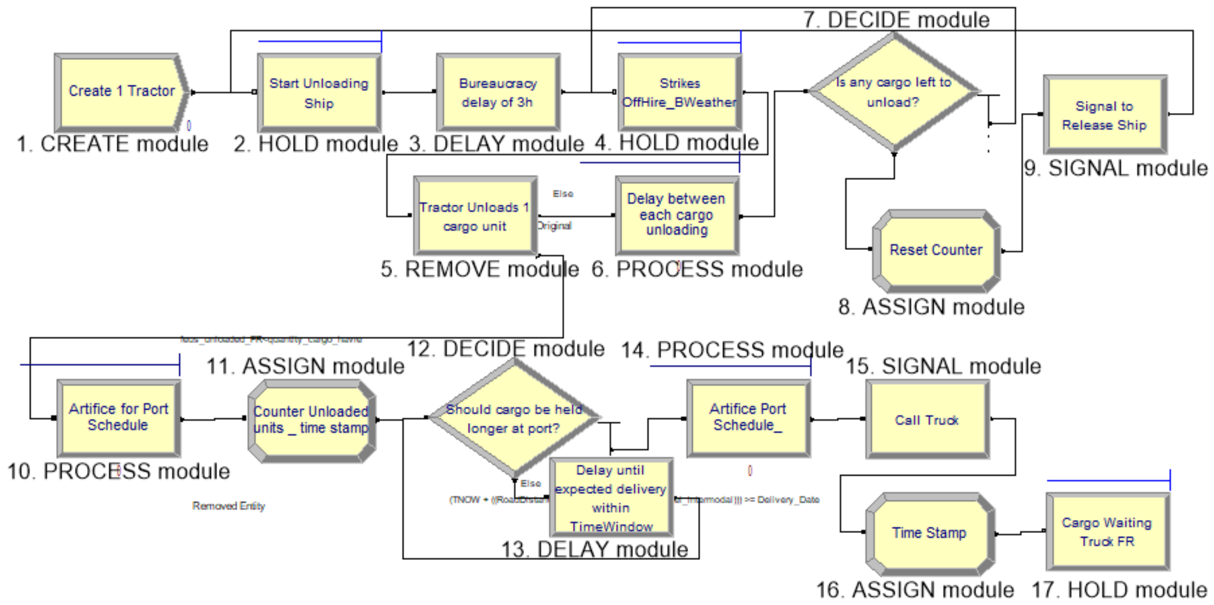


Figure 11 - ARENA submodel for cargo unloading in Le Havre.

The explanation of modules 1-17, shown in Figure 11, is as follows:

1. It is created one entity that represents the tractor that will unload the cargo from the ship.
2. This HOLD module is waiting for the signal sent when the ship arrives to port (in another part of the model), that will release the tractor (initiate the unloading operations).
3. Here, tractor is delayed for 3h to represent the bureaucracies involved before cargoes can be picked up by trucks.
4. This HOLD module is here to stop operations when a bad weather event or a strike occurs, thus, it only affects the process if one of these events are initiated.
5. The tractor, by entering this module, removes a cargo unit from the ship that is directed to module 10 and the tractor goes to module 6.
6. This module is used to hold the tractor for the time obtained by dividing 6 hours by number of cargoes to unload. This way, cargoes get ready to be picked up at a constant rate and the last one is released 6h after the first one and 9h after ship arrival to port. It also only allows the tractor to proceed its course when within the port opening hours.

(Tractor stays at module 6 temporarily, while cargo goes to module 10)

10. In this module the cargo unloaded from ship can only proceed its way when within the port opening hours (like in module 6).
11. This module is used to update the counter of unloaded cargo and assign the time stamp attribute (corresponding to the moment of unloading), both used to control the simulation.
12. Here it is estimated when cargo will be delivered if immediately picked up by a truck and if it is expected to arrive before time window, it is redirected to module 13. Otherwise, it goes to module 14.
13. Cargo is held until it is expected to be delivered within time window.

14. Like modules 6 and 10, cargo can only proceed when within port opening hours.
15. Sends a signal to the company to release a truck and a driver to pick the cargo up.
16. Assigns another time stamp attribute, corresponding to the moment cargo is ready to be picked up at the port.
17. Cargo is held here until the truck (and driver) arrive in the port and remove it from queue.

(Returning to the tractor process)

7. If there is not more cargo left to onload, the tractor returns to module 2 until next ship arrival. Otherwise, repeats the unloading process, returning to module 4.
8. When there is not any cargo left to unload, tractor enters this module to reset the counter of cargoes onboard to zero.
9. Sends a signal to the ship so it can depart from the port of Le Havre (returning to Leixões). End of cycle.

4.4 Model Validation

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 by the thesis supervisor professor Tiago Santos, having in mind similar transport solutions in Europe, regarding Intermodal Freight Transport and making use of Short Sea Shipping. The second one was extensively discussed with Professor Rui Carlos Botter (University of São Paulo).

The actual computer model validation was decomposed on three steps: verification, validation, and evaluation. Verification was done continuously during the modelling phase and involves debugging of the computer model and guarantying the program runs as planned. Validation compares the matching between the model and the real system under modelling, taking in consideration the assumptions and generalizations made. Usually, this comparison can be made using known data from the real-world system and the model's output. Although, this is not possible for the model developed since it focuses on the potential of the system and not to replicate one that already exists. Thus, the validation had to be done by *invalidation* [Quade (1980)], which consists in the systematic attempts of invalidating the model, i.e. prove it wrong. As this author stated, if it is tried all the reasonable invalidation procedures we can think of, we will not have a valid model, however we will have a good understanding of the strengths and weaknesses of the model, being able to be confident enough on the results obtained.

Evaluation consists in determining if the finished model meets the requirements set up. As mentioned before, the main objective is to investigate the potential of intermodal transport from northern Portugal to Northern France. It is concluded that the model is well adapted for this problem and for the input data set, the analysis conducted in the next chapters of this thesis 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. To complement that information, Figure 13 and Figure 14 show the locations of origins and destinations, respectively. The origins are located in Northern Portugal and destinations in Northern France, Belgium and Luxembourg. The distances by road and sea distances between cargo origins and destinations are specified later in this chapter, as well as all the uncertainties involved.

5.1 Transportation routes definition

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 chapter 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.

Such situation, that is, having to use unimodal transport instead of the intermodal due to lack of time, could be prevented by the company if it had a booking acceptance policy only up to a certain number of days before the actual delivery window. Although, since many costumers now operate with just in time strategies, it seems reasonable to accept bookings at short notice, shipping them by road when expecting to miss the delivery time window.

5.1.1 Intermodal (SSS preference)

The Intermodal service, as previously mentioned, is composed by a maritime route and 12 road legs, 6 in Portugal and 6 in France, connecting the ports with the origin/destination cities. SSS service is done making use of a Ro-Ro vessel, that will transport the semi-trailers from Portugal to France.

The sea route is approximately 600 miles long and was defined based on a study developed by Santos et al. (2019) for a potential route for a similar service, from Leixões to Le Havre.

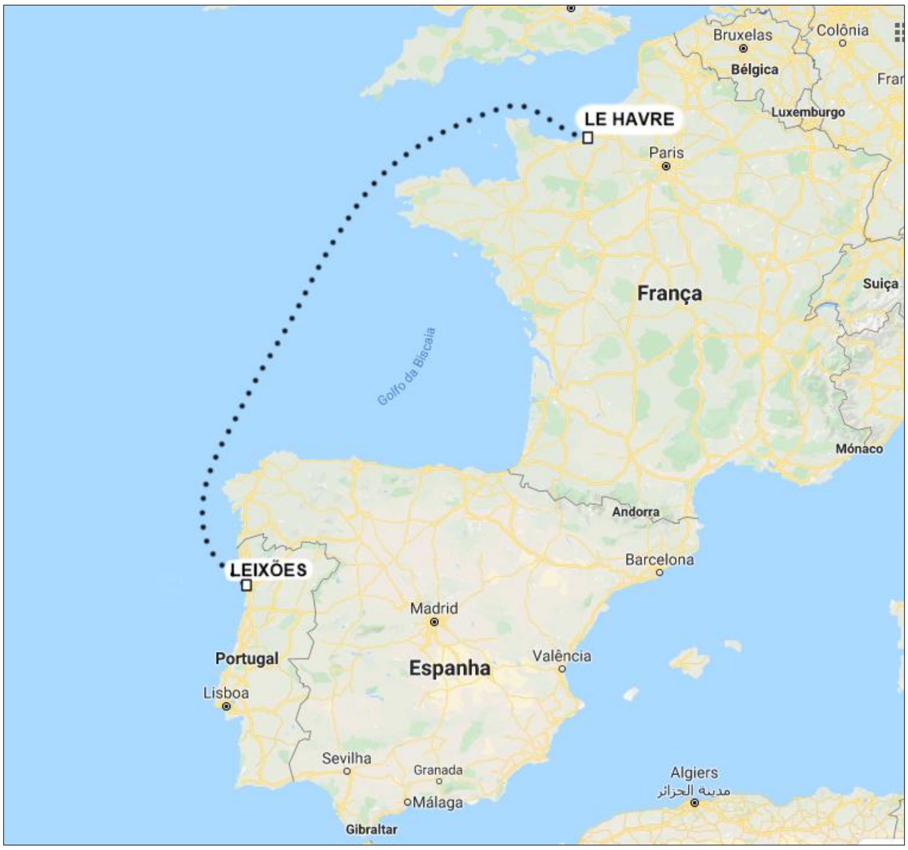


Figure 12 - Sea leg Leixões - Le Havre

The road legs considered were the same ones used by Santos et al. (2020), allowing the use of highways and choosing the most economical path. In Figure 13 is represented the intermodal road legs in Portugal and in Table 1 is specified the road distances between the multiple origins and the Port of Leixões.

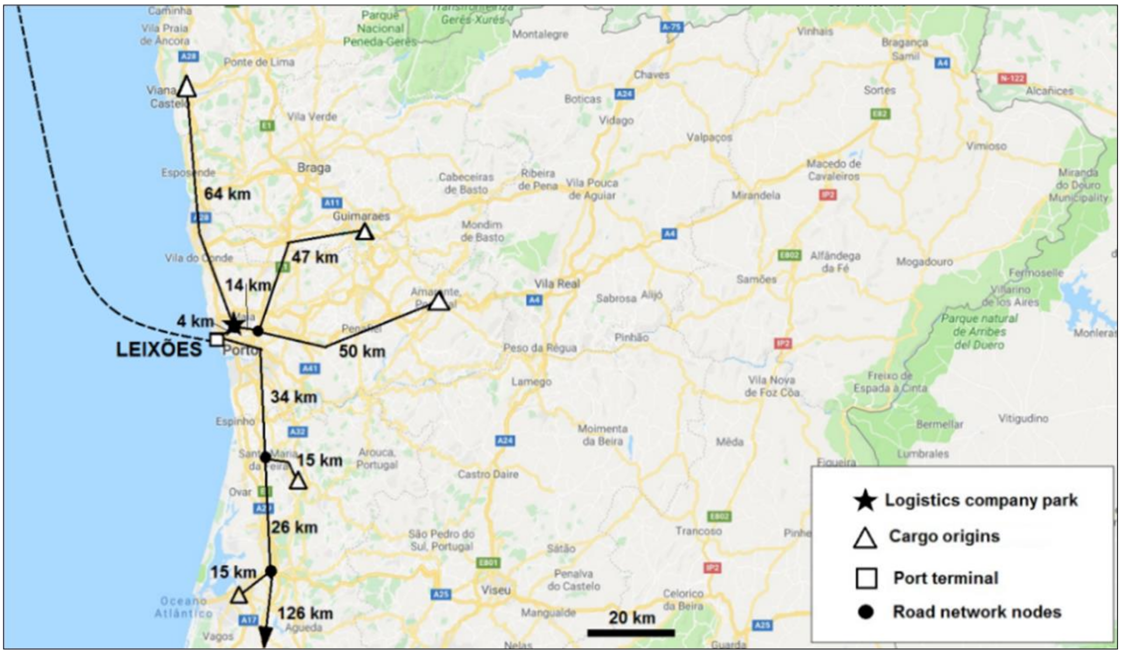


Figure 13 - Location of cargo origins in Portugal, loading port and logistics company truck park. Source: Santos et al. (2020)

Table 1 - Road distance between cargo origins and the Port of Leixões.

Distance [km]	Leixões
Viana do Castelo	68
Guimarães	65
Amarante	68
Oliveira do Hospital	49
Aveiro	75
Leiria	186

In Figure 14 is represented the intermodal road legs in Northern France; in Table 2 is specified the road distances between the Port of Le Havre and the multiple destinations.

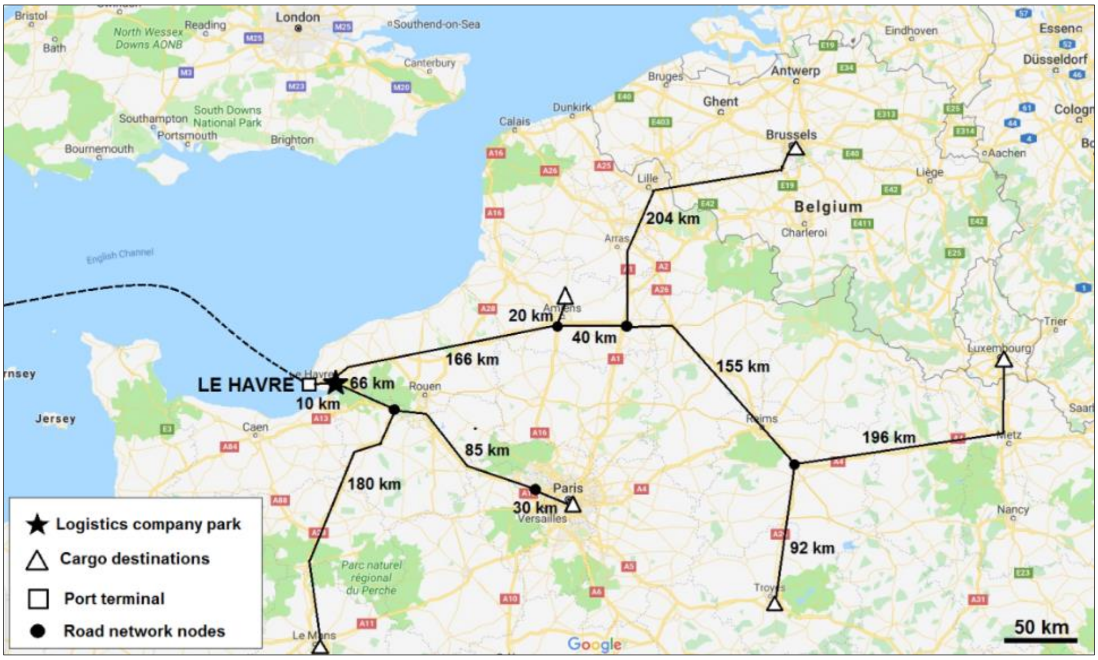


Figure 14 - Location of cargo destinations in Northern France, unloading port (Le Havre) and logistics company park. Source: Santos et al. (2020)

Table 2 - Road distance between the Port of Le Havre and cargo destinations.

Distance [km]	Le Havre
Brussels	420
Luxembourg	567
Troyes	463
Paris	191
Le Mans	256
Amiens	178

Semi-trailers can be dropped in the terminal from 2 days to 3h before scheduled ship departure. In the destination port, Le Havre, these may be picked up after some hours from ship arrival. That period between ship arrival and cargo pick up corresponds to the time spent in unloading operations and bureaucratic procedures before cargo are ready to leave the port. This can take 3 to 9 hours, thus, semi-trailers start to be available for pick up uniformly from the 3rd to the 9th hour after ship arrival. From the queue of ready trailers, the driver picks the most expected one to be delivered out of the time window.

Upon cargo delivery in the port of origin (Leixões) or in the cargo final destination, the driver and respective truck return to the logistic company's facilities in the region (located not far from each port).

5.1.2 Unimodal (Road service only)

The unimodal transport solution makes only use of road to take cargo from their origins in Portugal to their respective destinations in Northern France. This transport solution is approached and further studied here for two reasons. Firstly, because it is necessary to complement the intermodal transport solution for the cases that cannot answer the market demands (celerity related) and secondly, for being the most used solution nowadays for the transport problem described. Since it is intended not only to complement the intermodal solution but also to compare both solutions and ascertain their pros and cons, a full road service was developed as detailed below.

The road roots were developed resorting to Google Maps [Google (1)], identifying the most economical route which considers distance, time of journey and other possible extra costs, like tolls. The routes obtained are the ones represented in Figure 15.

Figure 15 - Road legs used in fully road based transportation.

Due to the location of the 6 origin cities, the borders used to enter Spain differ. Cargoes from Aveiro, Oliveira do Hospital and Leiria make use of the border with Spain via Vilar Formoso (Portugal) while the ones from Viana do Castelo, Guimarães and Amarante use the border close to Chaves (Portugal). After crossing these borders, both following road tracks head to the Franco-Spanish border near San Sebastian (Spain). Then, to Orleans (France) and in there the tracks split to connect with the multiple destinations.

The distances between each origin and destination are presented in Table 3.

Table 3 - Road distances between each origin and destination cities (full road).

Distance [km]		Destinations					
		Brussels	Luxembourg	Troyes	Paris	Le Mans	Amiens
Origins	Viana do Castelo	2053	2106	1833	1743	1605	1889
	Guimarães	1967	2020	1747	1657	1519	1803
	Amarante	1940	1993	1720	1630	1492	1776
	Oliveira do Hospital	1858	1911	1638	1548	1410	1694
	Aveiro	1961	2014	1741	1651	1513	1797
	Leiria	2138	2191	1918	1828	1690	1974

At the Franco-Spanish border and at the Paris periphery, the traffic is much intense, what leads to low road velocities. As so, it was considered that the truck velocities in these tracks were of 40 km/h.

5.2 Uncertainties affecting transportation operations

To approximate the simulation results to what happens in real life, it was adopted a series of uncertainties that affect system's behaviour. Variables like transit velocity, transport demand, delays caused by unexpected problems, etc cannot be predicted most of the times and even when it is communicated to a logistic company that something is not working correctly. Usually there is not much time to adapt the procedures and so, the service gets partially jeopardized. Thus, the uncertainties used will be described below.

5.2.1 Transport mode speeds

The ship velocity is generally 15 knots, however, in reality it is uncertain. In fact, weather affects the performance of the ship, hence, in winter (September to March) velocity tends to reduce. This way, it was developed the two velocity distributions presented in Figure 16, that were followed to assign a ship velocity in each voyage. The values adopted for these distributions are in line with the operational practices of a regular service currently in operation, connecting the ports of Leixões and Rotterdam.

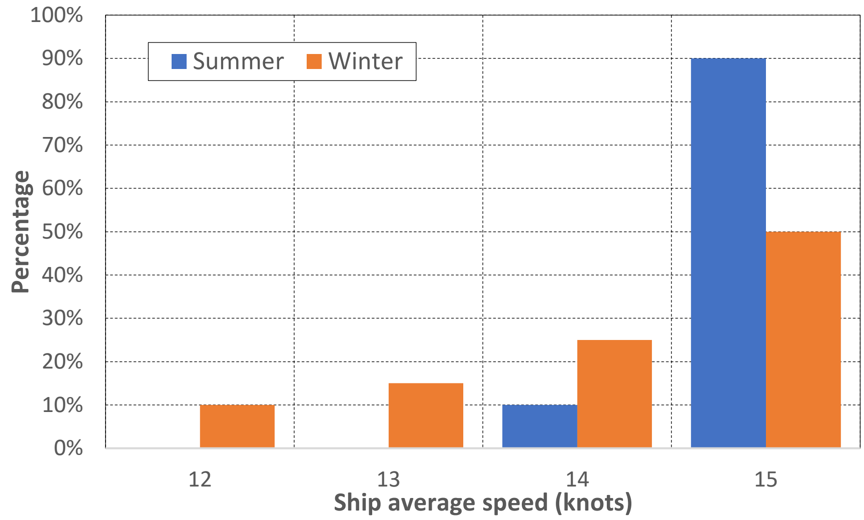


Figure 16 - Distribution of average ship speed in summer and winter.

The speed limit for trucks in highways differs in the three countries implied, varying between 80km/h and 100 km/h. In absence of real velocity data, it was defined two different discrete velocity distributions that seems qualitatively adequate: one distribution for intermodal road transport and another one for unimodal (full road) transport, with 75.7 km/h and 77.6 km/h of average speed, respectively, as presented in Figure 17. The discrimination between velocity distributions is due to the access to ports being usually congested so the speed distribution tends towards smaller values in intermodal service. In unimodal service, the great majority of distance travelled is in highways or equivalent, what leads to a shorter span of average velocities.

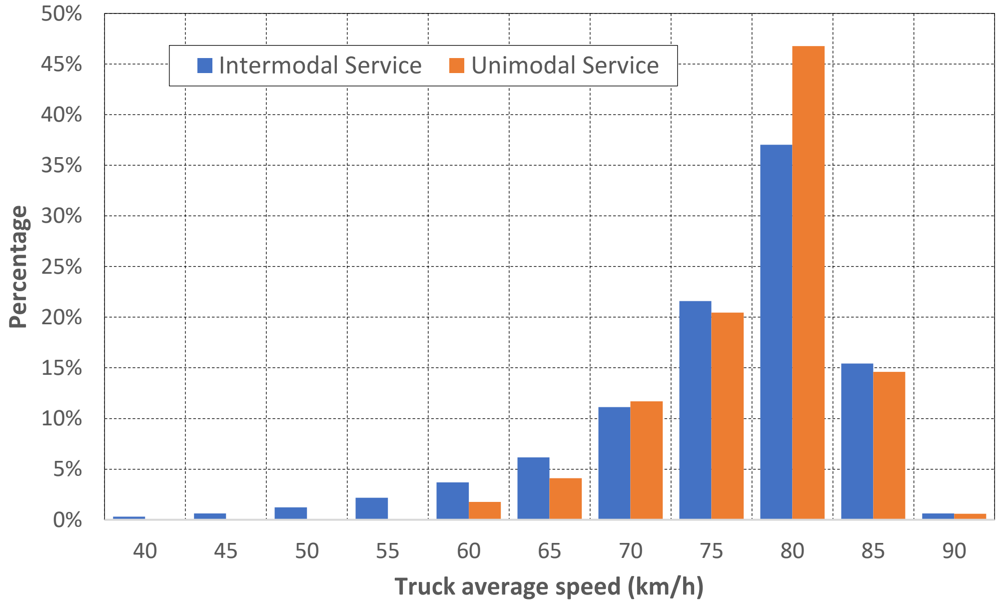


Figure 17 - Distribution of average truck speed in intermodal (pre-carriage and on carriage) and unimodal (long distance haulage) transport.

In Table 4, it is specified the probability density values for each truck velocity, presented in the previous figure. As mentioned before, the probability density function is narrower for the unimodal service.

Table 4 - Distribution of average truck speed in intermodal (pre-carriage and on carriage) and unimodal (long distance haulage) transport.

	Service	
Velocity [km/h]	**Intermodal**	**Unimodal**
40	0%	-
45	1%	-
50	1%	-
55	2%	-
60	4%	2%
65	6%	4%
70	11%	12%
75	22%	20%
80	37%	47%
85	15%	15%
90	1%	1%

In both transport solutions it is aimed to make the most efficient use of resources, that in this case are the drivers and trucks. The bigger the utilisation, the bigger the fatigue and as drivers have to rest mandatorily, trucks should stop as well for maintenance and cleaning activities. Thus, it was defined that at every 5000 kilometers travelled, the trucks go out of service for 24h so the cleaning and maintenance can be done.

5.2.2 Demand for transportation: geographical split of cargoes

There are six origins where cargo units are generated and six possible destinations for each one. All origins and destinations are cities at known distances from each port. Yearly, it was set a (fixed) total number of 2400 cargo units to be generated and the pairs origin-destination are fixed and presented in the following figure (and detailed in appendix 1):

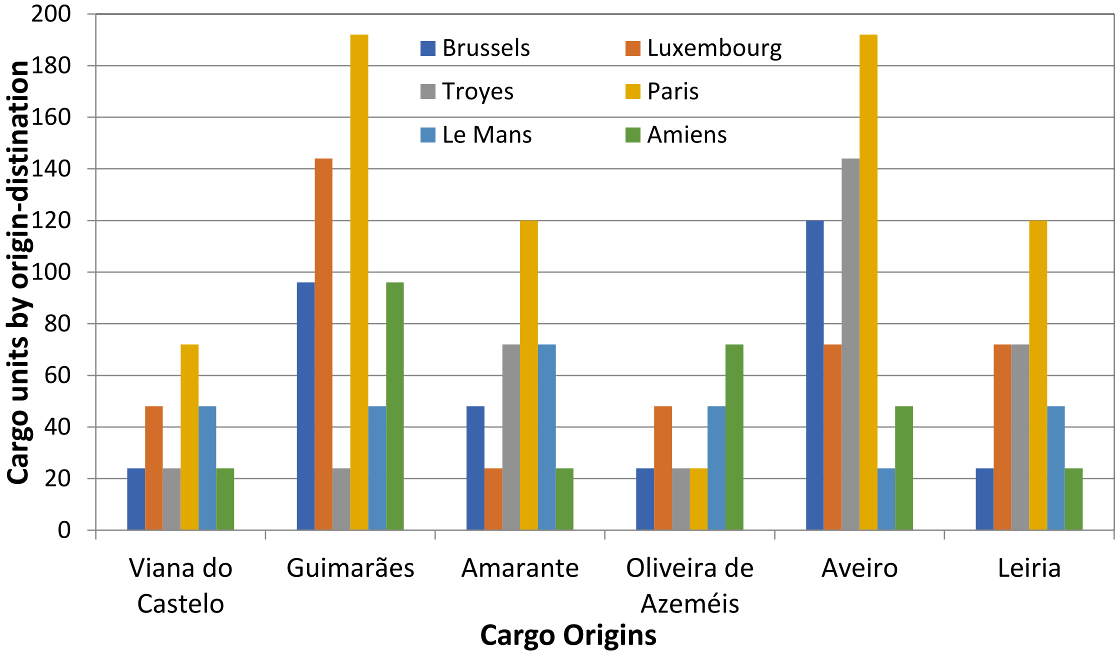


Figure 18 - Distribution of cargo units to be carried between pairs origin-destination.

The O-D pairs distribution were set accordingly to what is expected to be the approximate demand of each destination for typical exported Portuguese products and also taking into account the predominance of Portuguese communities, like in Paris and Luxembourg, where the demand is increased.

The occurrence of bookings (cargo generation) throughout each month is, however, uncertain. The demand for freight transport increases worldwide in Autumn (September to November), mostly because of Christmas in December. Hence, in these 3 months, 45% of the annual cargo is carried, being the remaining 55% carried in the other 3 quarters.

To every cargo unit generated, it is assigned a delivery date that varies from 4 to 9 days after generation, according to a random discrete distribution presented in Figure 19. It was set a delivery time window of 48h and so, cargoes should be delivered between the delivery date set and the end of this time window.

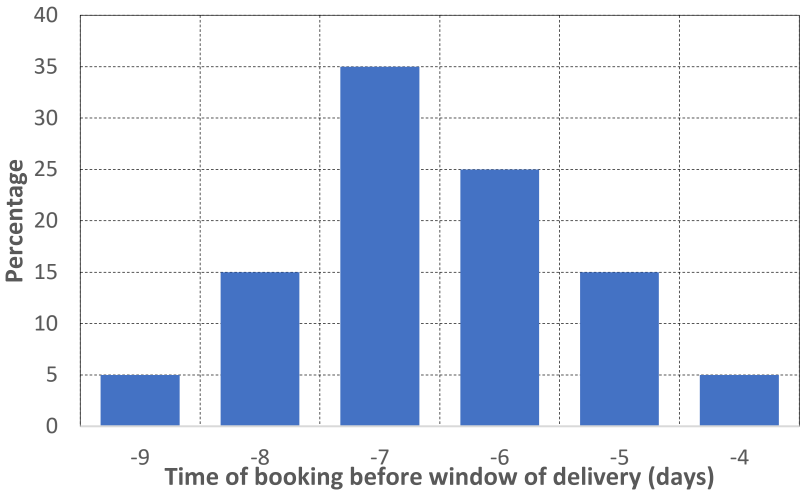


Figure 19 - Distribution of booking times in relation to contracted delivery time.

The system estimates the delivery date of each cargo via intermodal, based on average velocities, track distances, ship fixed schedule and on the expected average time spent in bureaucracies at each port. If the expected delivery date falls before the end of time window, the cargo is forwarded via intermodal transportation; otherwise, unimodal transportation is the alternative selected.

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). “Last minute bookings” mean bookings made in the day (24 hours) before the scheduled departure time, otherwise, cargo is forwarded to unimodal transport. In the high season (September to November) the ship operates at maximum capacity or close and 90% of times it is not able to accept last minute bookings. Out of the high season, the ship accepts 90% of the last-minute bookings. Time delay between trying to book space in the ship and the booking time in the logistics company is fixed at 6 hours.

Table 5 - Last minute bookings chances of acceptance over the year.

	Accepted [%]	Denied [%]
Sep-Nov	10	90
Dec-Aug	90	10

5.2.3 Bad weather events

Weather can turn out to be a major problem for transportation services, affecting all types of transport. This way, it was contemplated a bad weather uncertainty that compromises the ports operation and the road traffic in the northern European roads, as illustrated in Figure 20.

Figure 20 - Area affected by road closure due to bad weather events.

The destination city located more at south is the city of Troyes, which is not considered to be affected by the road closure events caused by the bad weather extreme conditions, when cargo is shipped via unimodal transportation. If it is shipped through the Port of Le Havre, it is affected as much as the remaining ones. Hence, cargo units shipped via unimodal to Troyes has a higher chance to be delivered within time window, although this nuance does not produce significant changes in the global results.

It was defined that it occurs two bad weather events per year, randomly and only during Autumn and Winter, causing the closure of both ports and northern European roads for 24h per each event. The random distribution followed was the discrete one below. Even in Autumn and winter, there are months when it is more likely to happen, hence, it was defined the discrete distribution presented in Figure 21.

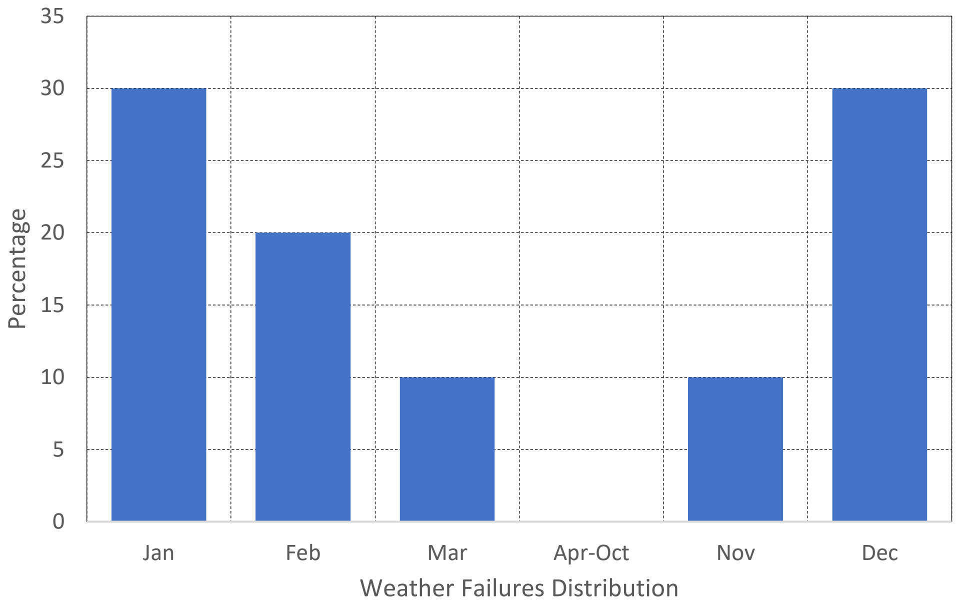


Figure 21 - Distribution of bad weather occurrences over the year.

5.2.4 Ship mechanical failures (off-hire)

As in any other vehicle, several types of problems can come up in a ship and some of them can compromise the service, interrupting it. So, it was defined that the ship gets stuck for 24h due mechanical failures twice a year. To assure that the failures affect the service, the system is set to activate failures right before each ship departure from Leixões, holding back every cargo 24h, what will cause deliveries to destination outside time window for many ones. The distribution type used was the uniform one.

5.2.5 Port strikes

It is frequent to see news regarding strikes in ports around the world, usually taken by lower class workers under precarious conditions. When a strike occurs, normally there is a big adherence by the members of the class that issued the strike, causing the impossibility for the port to keep labouring, lead to its temporary closure. So, during a strike, cargo cannot be accepted or released from the ports, as well as the ship loading or unloading operations that are interrupted. Comparably to ship mechanical failures, the uniform distribution was the type used and it was defined that strikes occur twice a year, lasting 24h each as well.

5.2.6 Ship departure delays

As mentioned before, in chapter 3, frequently the ship departure time schedule is not respected due to bureaucracies regarding cargo and the port and ship services in general. The bigger the demand, the bigger the departure delay. This way, it was defined two discrete random distributions that sets the day for each voyage, one for Autumn (from September to November) and another for the remainder months.

The distributions are asymmetric, and it is considered that the ship only departs after the time scheduled, never before. In the figure below, it is represented these distributions.

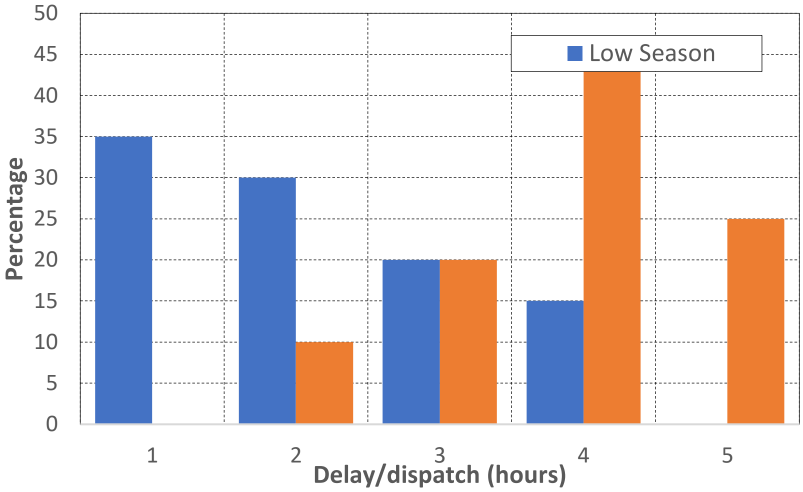


Figure 22 - Distribution of delays in departure time from port.

5.3 Internal costs calculation

Through the data collected by running the simulation, it was possible to calculate the costs of the logistic company when making use of the intermodal or unimodal solutions. It was followed the same cost structure presented by E. Tzannatos, S. Papadimitrious (2014) and Sambracos and Maniati (2012), being considered the capital costs, fuel costs, tolls, insurance, driver wages, truck maintenance and road circulation taxes. The fleet of trucks is fixed in each simulation but the effects of variations in its size in terms of costs and transport time reliability may be evaluated.

5.3.1 Unimodal service

In the table below, it is presented the fixed costs relative to road transport. The acquisition of a new truck involves an initial capital investment and associated loan expenses over the years. These correspond to an annualized capital investment cost equal to 7805€ for each truck.

Table 6 - Fixed costs of road service

Fixed Costs		new truck	120,000	€
	Assuming	annual interest rate	5	%
		repayment period	25	years
		residual value	10,000	€
		annualised capital investment costs	**7,805**	**€/year**
		driver's annual cost [intermodal]	25,284	€/year
		driver's annual cost [unimodal]	30,000	€/year
	Vehicle	insurance	3,000	€/year
		administration cost	2,400	€/year
		MOT	70	€/year
		road tax	1,320	€/year

In terms of variable costs, it is considered the maintenance and cleaning operations, the fuel cost, lubricants and tire replacements, which are specified in the following table.

Table 7 - Variable costs of road service.

Variable Costs	Maintenance & Cleaning	2,000	€/year
	Fuel	0.56	€/km
	Lubricants	0.1	€/km
	Tire replacement	600	€/tire
	Tooling	See tables 8 to 10	

The fuel cost estimation was based upon an average consumption of 0.4 L/km and diesel fuel cost of 1.4 €/L and the tires replaced at every 60,000 km.

When cargo is expedited via intermodal transportation, the truck departs from the logistic company's facilities, goes to cargo origin to pick it up, then to the Port of Leixões and returns to companies facilities. Otherwise, being shipped by road only, until cargo pick up it is the same but from there the truck goes directly to destination. As the routes differ in both solutions, the tolls applied differ as well. To calculate tolls, it was used adequate websites of each country for each pair OD and considering a 5 axes truck as the vehicle. Tolls assessed in [Tolls (2020)].

The first track, from truck fleet park to cargo origin, is common to both intermodal and unimodal solutions. The toll costs in the table below represent one-way trip for each cargo origin.

Table 8 - Tolls' cost betwee cargo origin and the Port of Leixões (Intermodal).

Tolls [Park - Cargo Origin]		
Cargo Origin	**Cost**	
Viana do Castelo	9.65	€/trip
Guimarães	8.30	€/trip
Amarante	10.35	€/trip
Oliveira do Hospital	15.30	€/trip
Aveiro	12.20	€/trip
Leiria	31.75	€/trip

As the truck fleet park is close to the Port of Leixões, for the intermodal solution, the voyage to bring the cargo to the port is done using the same highways. Thus, the round-trip tolling cost is the double of the presented in the table above. For unimodal, the truck after picking the cargo up, heads to Spain by the more economic route according to *Google Maps*. Routes from Viana do Castelo, Guimarães and Amarante use the border in Vila Verde de Raia and the remaining ones the border in Vilar Formoso. The tolls were calculated for each border used and are presented in the following table.

Table 9 - Tolls' cost between cargo origin and corresponding PT-SP border.

Tolls [Cargo Origin – PT-SP Border]	
Cargo Origin	**Cost**
Viana do Castelo	31.65 €/trip
Guimarães	19.40 €/trip
Amarante	13.20 €/trip
Oliveira do Hospital	34.50 €/trip
Aveiro	34.50 €/trip
Leiria	55.30 €/trip

The tracks of the routes in Spain start from one of two borders with Portugal and end all in the same border with France, in Irun. In Spain tolls are almost non-existent, when compared to Portugal, being paid only one section of the highways used. This section is common to every route and has a toll cost of 32.02€.

From the Spain-France border on, the tolled highways are quite significant, being the total amounts applied the ones in the following table, depending on the destination.

Table 10 - Tolls' cost between SP-FR border and cargo destination.

Tolls [SP-FR Border - Destination]	
Cargo Destination	**Cost**
Brussels	219.10 €/trip
Luxembourg	242.20 €/trip
Troyes	229.60 €/trip
Paris	174.90 €/trip
Le Mans	127.70 €/trip
Amiens	202.30 €/trip

For each cargo unit delivered outside time window, it is considered that the logistic company has to pay a fee to the costumer in order to compensate the constraints caused by the delivery delay. of 400€ per each late day or fraction, i.e., if a cargo is delivered 24h or less after time window, it is applied a fee of 400€.

5.3.2 Intermodal service

The SSS service makes part of the intermodal solution and so, road service is still necessary. The annual internal costs of road service have the same cost structure as the unimodal solution, with exception for drivers' salaries, which have not the long haul compensations/subsidies.

As this study is made from a perspective of a logistic company, the ship cost structure is not developed in detail since the sea leg is outsourced, being considered a fixed price for each cargo unit transported of 750€, as used by Santos et al. (2019) for a similar service with identical characteristics.

5.4 Performance requirements of the transport solutions

As it has been stated in subchapter 3.4, KPI were defined to express how well the system is behaving taking into consideration the goals to fulfil. Thus, it is considered that to be efficiency competitive, the reliability of the transport solution would have to comply with a minimum of 95%. Then, the total cost should be minimum, trying every possible combination of quantities of entities – configurations.

It is also to measure the average transit time for each pair origin destination for the various configurations, as well as the utilisation of the utilisation of each truck types and drivers should be maximum.

6. NUMERICAL SIMULATION RESULTS AND DISCUSSION

6.1 Transport System Configurations

It should be recalled that the simulation model takes the perspective of a logistic company that uses a combination of the intermodal and unimodal solutions. The simulation model was therefore run for several configurations, which differ from each other in the number of resources of each type (specified in 4.1.1 Elements of the simulation model). As there are five entity types as entities (drivers and trucks) in the system (which are also denominated resources), testing every possible combination would imply running the simulation for thousands of configurations, which is clearly impossible to execute considering the time of each simulation, presented in Table 11.

Table 11 - Computer technical specifications and simulation time.

Processor	Intel® Core i7-4510U
Random Access Memory (RAM)	8GB
Hard Disk Drive	500GB SSD
Operative System (OS)	Windows 10 Home © Microsoft Corporation
Time of Simulation	98 minutes and 78 seconds (20 iterations)

It is noteworthy that the system needs all five entity types to work effectively and an absence or not enough quantity of an entity type can create 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 one to five 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.

The simulations are set to start on May 7th and have a duration of three hundred and sixty-five days. In order to get reliable results for each configuration, it was observed that with twenty iterations the system is perfectly stabilized, that is, the calculations computed for the reliability obtained would not change significantly with further iterations. Figure 23 shows the reliability obtained depending on the number of iterations and supports this conclusion.

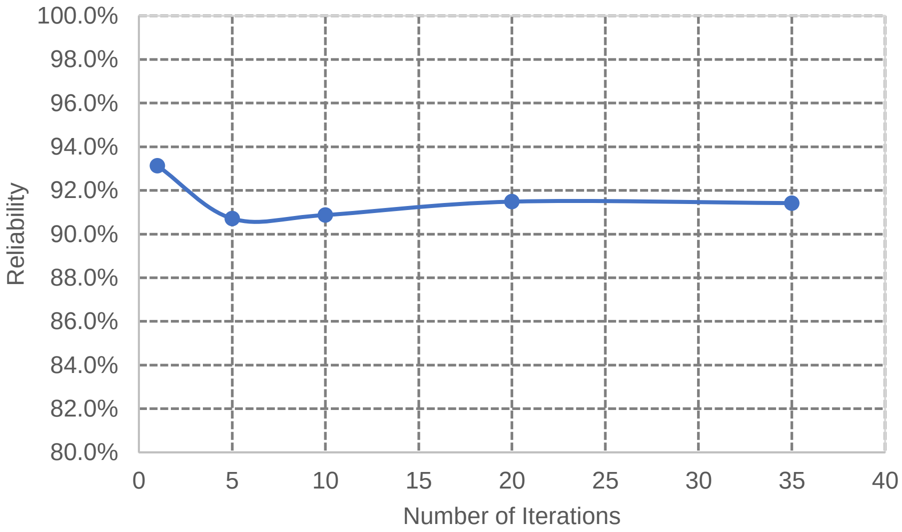


Figure 23 - Average reliability as a function of the number of iterations.

6.1.1 Intermodal

As mentioned in the beginning of this chapter, it was not doable to simulate every possible configuration of an intermodal solution and so, to filter configurations with certain amounts of resources that would be discarded anyways, several configurations were simulated with considerable progressive variations in their resources, until it was reached the reliability outcome of 95% or more. Then, analysing the utilisation of each resource over time, it was possible to infer which entity quantity could be changed, obtaining at least 95% of reliability and simultaneously the lower total cost possible.

In the table below it is presented the configurations simulated in a first batch. The ones which outputted a reliability over 95% are highlighted.

Table 12 – Intermodal configurations simulated (first batch)

Configuration	E1	E2	E3	E4	E5	**Reliability**	**Total Cost**	% Intermodal	Cost/unit cargo	Late deliveries (days)
1	8	15	11	16	8	93.16%	6,889,703 €	77%	2,871 €	269
2	8	14	11	15	8	87.67%	6,649,734 €	77%	2,771 €	1296
3	8	15	12	16	8	92.15%	7,024,303 €	77%	2,927 €	436
4	8	15	10	16	8	91.49%	6,872,067 €	77%	2,863 €	361
5	8	15	12	16	9	91.90%	7,034,860 €	77%	2,931 €	421
6	8	14	10	16	8	91.34%	6,229,539 €	78%	2,596 €	377
7	8	14	9	16	8	83.33%	6,887,587 €	78%	2,870 €	667
8	8	14	10	16	7	83.69%	6,942,050 €	77%	2,893 €	659
9	8	20	15	20	12	98.69%	6,526,760 €	77%	2,719 €	34

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)

The configurations with reliability results under 95% cannot be considered since the first KPI specified is not fulfilled.

Before defining more configurations, it is possible to take some conclusions. In configuration 9, the system works almost perfectly, having only 34 days of late delivery[4] in 2400 cargo units shipped. Although, the average utilisation ratios observed were a under the maximum capacity, as it can be seen in figures from Figure 24 to Figure 28.

The utilisation measured correspond to the high season, from September to November, since this is a critical period due to the amount of cargo that needs to be shipped. Also, the utilisation figures presented are of average utilisation results at approximately the same time during the approximately 12 weeks of the high season.

In Figure 24 and Figure 25 are presented the utilisation over time of trucks and intermodal drivers based in Portugal. Trucks based in Portugal and Intermodal drivers that transport cargoes from their origins to the Port of Leixões, reach their picks of utilisation before each ship departure but at slightly different times though. That is, 24 hours before ship departure the ship start not accepting the majority of the cargo generated (last minute bookings) and so, the utilisation of intermodal drivers drops down but the trucks' increases, since that cargoes have to be shipped by road only and the trucks used for that are the same. Right after each ship departure, the chances of a cargo of being admitted for intermodal transportation are quite low as well, since it takes 7 days for the next ship departure, plus around 2 days more to arrive to Le Havre and averagely 13 hours more to go from there to the destination. Thus, from 1 to 5 days, approximately, before ship departure the utilisation of intermodal drivers lowers to the minimum and the opposite happens to the utilisation of trucks.

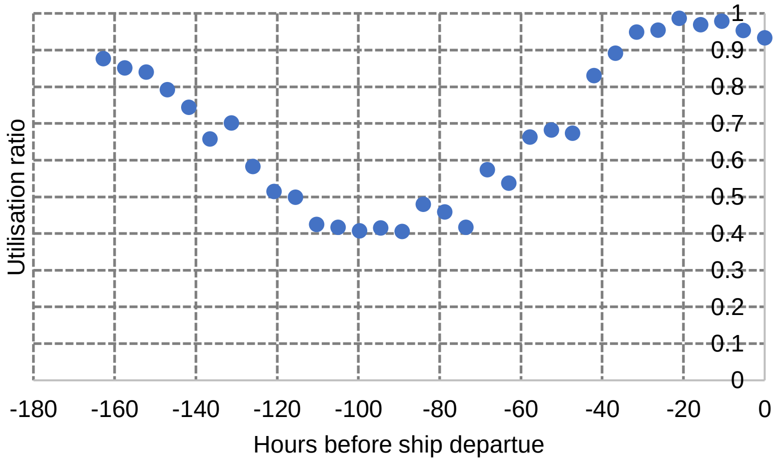


Figure 24 - Average utilisation of trucks based in Portugal during the high season weeks in configuration 9.

[4] days of late delivery does not correspond mandatorily to the number of cargoes that arrived outside the time window, since one cargo can be delivered with more than one day of delay.

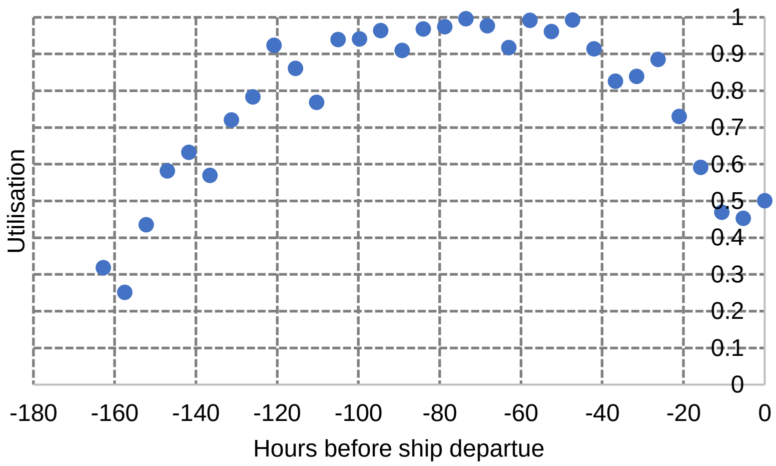


Figure 25 - Average utilisation ratios of intermodal drivers based in Portugal during the high season weeks in configuration 9.

In Figure 26 it is presented the utilisation results but for unimodal drivers, that take cargo from Portugal to Northern France by road only.

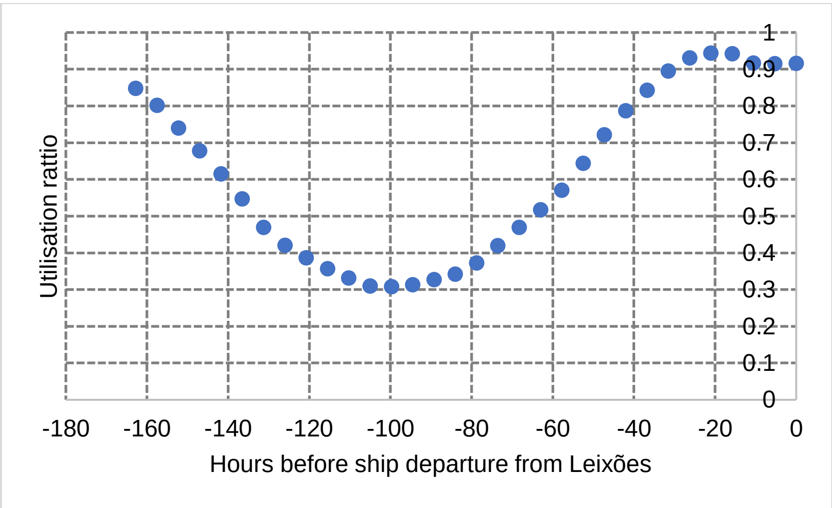


Figure 26 - Average utilisation ratios of unimodal drivers during the high season weeks in configuration 9.

As it was expected, the plot obtained is symmetrical to the one in Figure 25, since both services complement each other. When the cargoes generated are being admitted for intermodal transport, unimodal driver's utilisation drops down drastically and rises when it is too late or too soon for intermodal shipping.

When in France, the logistic company makes use of trucks and intermodal drivers that are based in Le Havre to take cargoes from the port to their final destinations. The utilisation ratio measured for these resources is presented in Figure 27 and Figure 28.

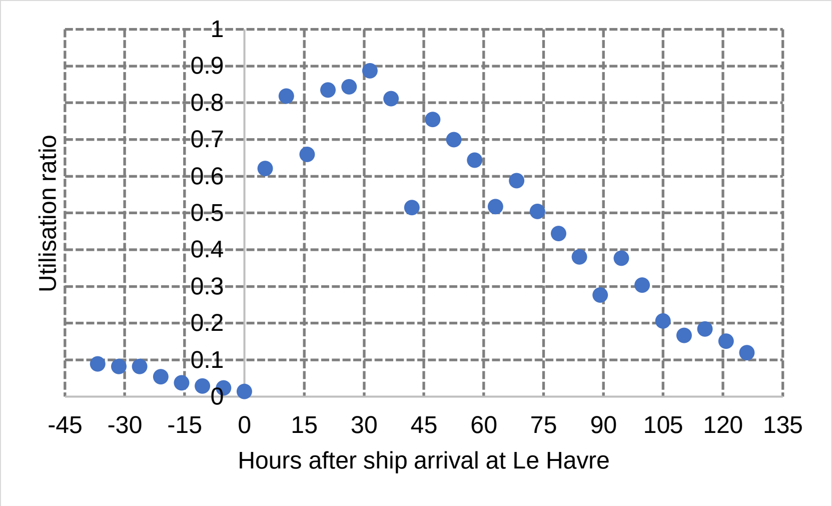


Figure 27 - Average utilisation ratios of trucks based in France during the high season weeks in configuration 9.

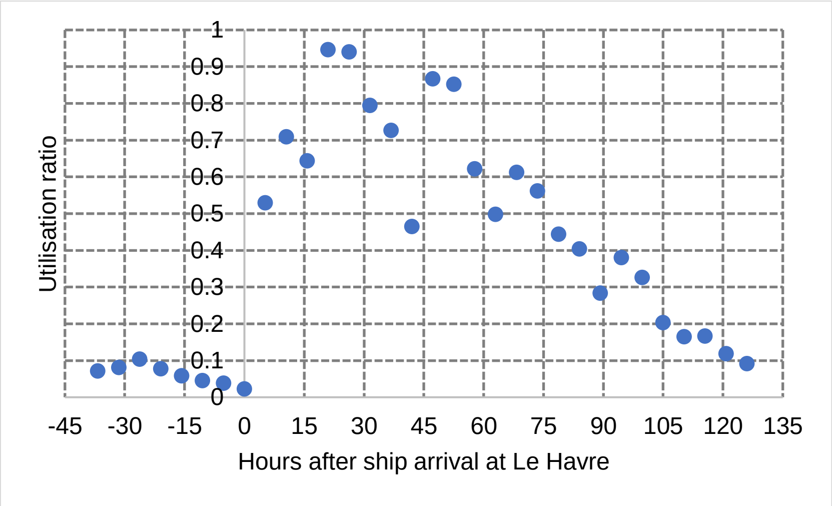


Figure 28 - Average utilisation ratios of intermodal drivers based in France during the high season weeks in configuration 9.

When ship arrives in the Port of Le Havre, bureaucracy procedures are done and only between 3 to 6 hours after ship arrival, cargoes are ready to be picked up by the trucks. Although, if the system estimates a delivery before the time window (in the destination), the cargo is held at the port temporarily until the time window is open. This explains the utilisation dispersion present in both figures above since the cargoes are not released from the port all at the same time.

As the trucks in France are only used for the intermodal service, their utilisation plot is not much different from the driver's one. The differences, in terms of operation, between trucks and drivers are that trucks enter in off service for maintenance for 24h and drivers in daily and/or weekly rests out the voyages for 11h and 45h, respectively. This explains the small differences between both plots. Nevertheless, it is observed that both trucks and drivers based in France incur in underutilisation over the week, since the utilisation picks reaches 0.9 (or close to) but not for long. The utilisation of these entities after ship arrival is mostly around 0.8, what indicates that most of the time 3 or 4 units of each entity type are available.

After the entity utilisation analysis above-mentioned and the slight underutilisation of some entities observed, it was decreased the quantities of every entity, except the first one (E1), and the configuration 10 was created. It was verified a small decrease in both total cost and reliability. As reliability decreased, it was observed an increase of the entities' average utilisation, as well. Thus, it was decreased again the quantities of each entity and configurations 11 to 19 were created. This configuration creation process was based on decreasing the quantities of an entity that exhibits a underutilisation, until the reliability requirement is not satisfied anymore.

Table 13 - Intermodal configurations simulated (second batch)

Configuration	E1	E2	E3	E4	E5	**Reliability**	**Total Cost**	% Intermodal	Cost/unit cargo	Late deliveries (days)
10	8	18	14	20	11	98.41%	6,429,378 €	78%	2,679 €	40
11	8	18	13	18	11	96.82%	6,434,622 €	77%	2,681 €	105
12	8	18	12	18	10	97.48%	6,349,793 €	77%	2,646 €	69
13	8	17	12	18	9	96.91%	6,321,873 €	77%	2,634 €	85
14	8	17	11	18	9	96.85%	6,270,456 €	77%	2,613 €	84
15	8	17	11	18	8	96.50%	6,271,245 €	77%	2,613 €	98
16	8	17	11	18	7	92.96%	6,272,017 €	78%	2,613 €	182
17	7	17	11	18	9	88.81%	6,681,931 €	75%	2,784 €	792
18	7	17	12	18	9	87.67%	6,648,640 €	74%	2,770 €	1033
19	7	18	10	19	7	89.59%	6,519,042 €	74%	2,716 €	418

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)

If configurations 17, 18 and 19 are closely analysed, it gets clear that with less than 8 Portugal based intermodal drivers (E1), the system starts jeopardizing intermodal service and consequently, creating an overload in the unimodal since it is verified an increase on the intermodal share from configuration 16 to configuration 17 (see utilization plots of configuration 18 in appendix 2). In configuration 19 it was tried to compensate the increase of intermodal share by increasing the quantities of trucks (PT) and unimodal drivers, although it turned revealed to be more expensive and under the reliability requirements than in the conditions of configuration 14. Unimodal service turns out to be more expensive and so, the smaller the share of intermodal service, the bigger the total cost gets. Therefore, it requires 8 intermodal drivers (PT), regardless of the remaining fleet sizes.

Having a reliability of 95% or more, it is intended to find the configuration that correspond to the lower total cost. In the configurations above, the configuration that fits better to this is configuration 14, with a reliability of 96.85% and total cost of 6,270,246€.

Nevertheless, it may not be the configuration that fits best the goals established. Although, before defining more configurations and simulating them, it should be again carefully analysed the utilisation plots of every entity. Autumn is the high season and consequently the relevant utilisation plots for analysis are the ones within this period.

In order to not just analyse the utilisation measurements of configuration 14 but also to evaluate the impact of the changes made, it will be presented the results of configuration 9 too. In the figures below, it can be compared how the utilisation changes over time, during the high season, in configurations 9 and 14.

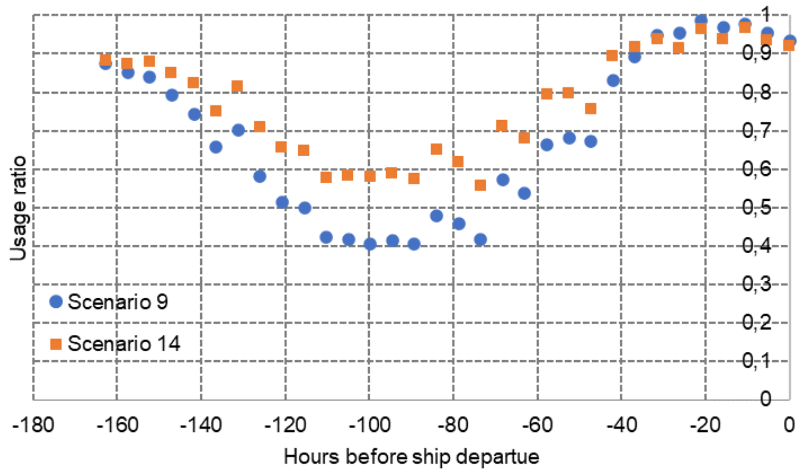


Figure 29 - Average utilisation ratios of trucks based in Portugal during the high season weeks in configurations 9 and 14.

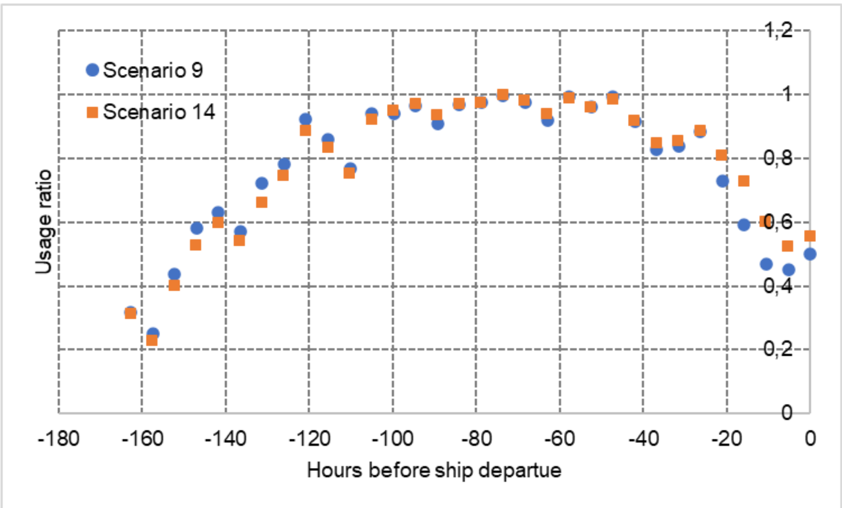


Figure 30 - Average utilisation ratios of intermodal drivers based in Portugal during the high season weeks in configurations 9 and 14.

Both plots above are like their analogous in configuration 9 and their interpretation is identical. The number of intermodal drivers based in Portugal did not change, hence, the utilisation over time did not change either, having just some small fluctuations like right before ship departure from Leixões but none worthy of a deep analysis.

On the other hand, the number of trucks decreased from 20 (configuration 9) to 18 (configuration 14) and this changed the utilisation, as it can be observed in Figure 29. Between two ship arrivals, the minimum utilisation was of around 0.4 in configuration 9 and of 0.6 in configuration 14 and generally at all instants the utilisation increased.

In Figure 31 can be analysed the utilisation plot obtained for unimodal drivers for configuration 14 and compares it with the one from configuration 9.

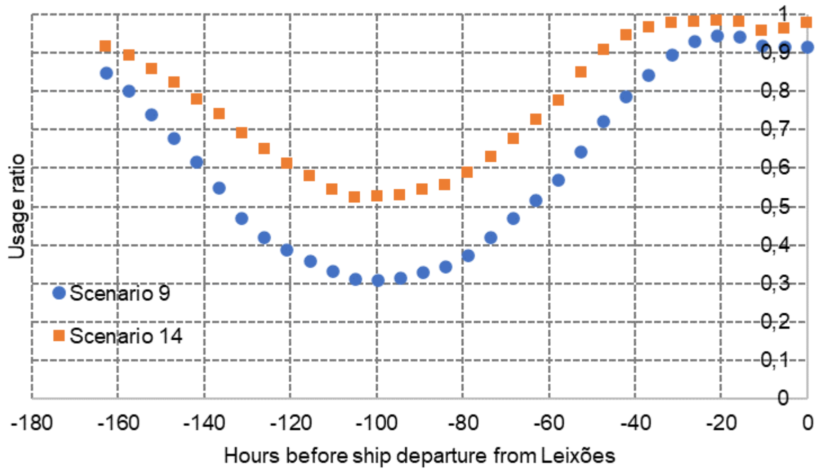


Figure 31 - Average utilisation ratios of unimodal drivers during the high season weeks in configurations 9 and 14.

Once again, by decreasing in 3 the number of unimodal drivers from configuration 9 to 14, the utilisation in general increased, as well as the minimum obtained between two ship arrivals, from around 0,3 to 0.5. It can be denoted that in general the utilisation increased and was maximum (or very close to) for longer, for example, 40 hours before the ship arrival, in configuration 9 the utilisation was of approximately 0.8 and 0.95 in configuration 14, persisting until ship arrival. It is likely that 40 hours in maximum utilisation is very close to generate a bottleneck and it is something to be investigated later on.

To complete the intermodal service, in France, drivers and trucks take cargoes from the port to their final destinations. In configuration 9, the maximum utilisation rates of trucks and drivers based in France barely reached 0.9, thus, it was also reduced the quantity of these in 3 and 4 units, respectively. The utilisation plots obtained for these entities are presented in Figure 32 and Figure 33, for both configurations.

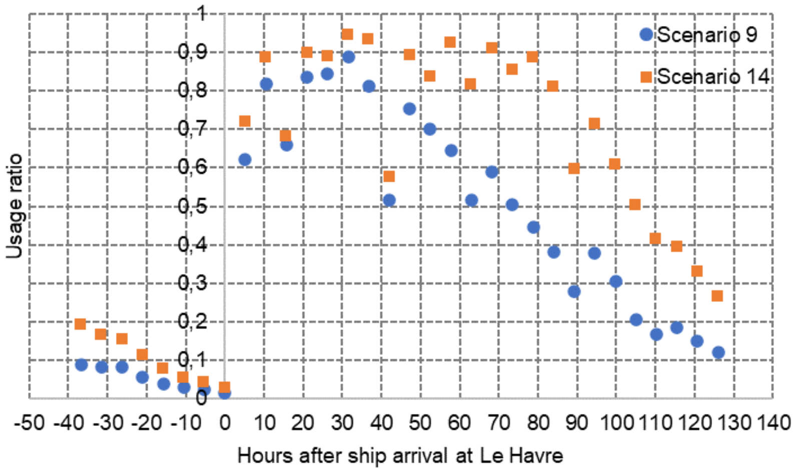


Figure 32 Average utilisation ratios of trucks based in France during the high season weeks in configurations 9 and 14.

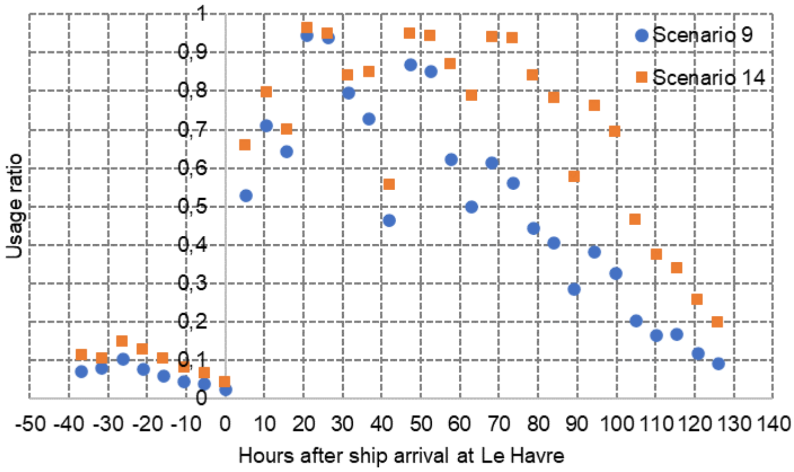


Figure 33 - Average utilisation ratios of intermodal drivers based in France during the high season weeks in configurations 9 and 14.

As can be noted, in both figures can be identified general fluctuation in terms the utilisation obtained when comparing configuration 14 to configuration 9, what made the average utilisation increase considerably. Also, it is visible that after ship arrival, the utilisation of both entities is generally above 0.9 for around 80 hours, what indicates that they are reaching the limit to overload, creating a bottleneck.

Nevertheless, configuration 14 cannot yet be taken as the best alternative of lowest cost with more than 95% of reliability, since it may exist similar configurations that produce slightly better results and so, small changes were made and the configurations presented in Table 14 were simulated.

Table 14 - Intermodal configurations simulated (third batch)

Configurations	E1	E2	E3	E4	E5	**Reliability**	**Total Cost**	% Intermodal	Cost/unit cargo	Late deliveries (days)
14	8	17	11	18	9	96.85%	6,270,456 €	77%	2,613 €	84
20	8	17	11	18	10	97.23%	6,297,996 €	77%	2,624 €	74
21	8	17	11	19	9	97.24%	6,286,320 €	78%	2,619 €	71
22	8	17	12	18	9	96.91%	6,321,873 €	77%	2,634 €	85
23	8	18	11	18	9	96.72%	6,341,115 €	77%	2,642 €	91
24	9	17	11	18	9	97.64%	6,282,722 €	78%	2,618 €	60
25	9	17	11	18	10	97.67%	6,297,285 €	78%	2,624 €	59
26	9	17	11	19	9	97.77%	6,296,047 €	78%	2,623 €	55
27	9	17	12	18	9	97.77%	6,311,744 €	78%	2,630 €	57
28	9	18	11	18	9	97.68%	6,306,576 €	78%	2,628 €	59
29	10	17	11	18	9	97.57%	6,292,365 €	78%	2,622 €	62
30	9	16	12	18	9	97.12%	6,292,598 €	78%	2,622 €	75
31	9	16	12	17	9	96.84%	6,277,527 €	78%	2,616 €	90

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)

Configurations 20 to 24 were created by increasing one unit of each entity separately to ascertain how the reliability and total cost would change. It was expected that the number or late delivery days to decrease, and consequent amount paid, and/or the intermodal service share would increase. This would, in the one hand, lower the costs in the other hand, increase them since more entities in the system result in a cost increment. So, the point was to verify which cost change would prevail.

As it can be concluded, by analysing the results in Table 14, there was not obtained a configuration that could beat configuration 14 in terms of total cost. Despite the slight improvements in reliability, as the requirement of 95% was already fulfilled in configuration 14, the total cost lowering is now the priority.

Then, configurations 25 to 29 were created with the purpose of increasing the intermodal share, since it is more cost effective than the unimodal. So, it was increased in one unit the number of intermodal drivers based in Portugal (E1) and similarly to configurations 20 to 24, it was then increased one unit of each entity separately to ascertain how the reliability and total cost would change. Once again, the cost reduction caused by the decrease in late deliveries and by the intermodal share increase did not prevail over the cost increment associated with the addiction of more entities.

Configurations 30 and 31 were defined with the purpose of maximize the intermodal share by increasing the number of intermodal entities and consequently reducing the number unimodal drivers since their demand would decrease. As it can be observed, it did not turn out more advantageous than configuration 14. In the following figure, it can be better analysed the dispersion in the reliability and cost results presented in Table 14.

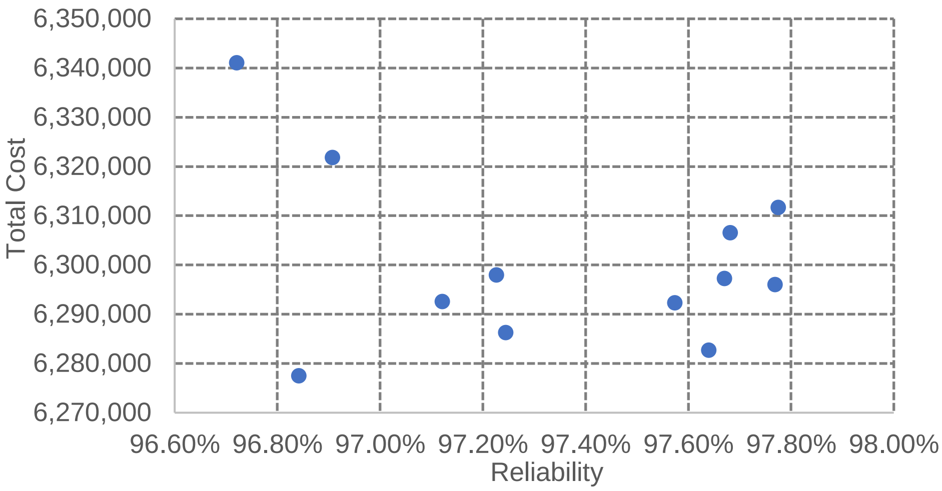


Figure 34 - Total cost and reliability of intermodal configurations 20 to 31.

From another analysis point of view, it may look odd the comparison between the results obtained for configurations 24 and 29, since the reliability decreased in the last regardless of having one more entity E1 and the same quantities of the remaining ones. The reason to justify this outlier is for example, the predominance of bad weather events, strikes or ship mechanical off-hire during the high season in configuration 29 and not so much in configuration 24. Despite of the 20 iterations performed, it is still admissible the existence of some tiny discrepancies like this one.

6.1.2 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.

First it should be found the best combination of entities (configuration) so the reliability and the lowest total cost requirements are fulfilled. Then, compare the best configurations of each modality through the first three KPIs listed in section 3.4, that are the following:

1. Reliability of the transport solution expressed as the percentage of deliveries within time window in destination cities per year – minimum of 95%,
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,

In the table below are presented the configurations simulated in a first batch. In the first batch, the quantities of each configuration were incremented in 5 units at a time until the performance requirement of 95% was fulfilled. The configurations that outputted a reliability over 95%, from here on, are highlighted in green.

Table 15 - Unimodal configurations simulated (first batch)

Configuration	Unimodal Drivers	Trucks (PT)	**Reliability**	**Total Cost**	Cost/unit cargo	Late deliveries (days)
1	30	25	27.05%	35,673,286 €	14,864 €	65832
2	35	30	34.23%	23,763,092 €	9,901 €	33728
3	40	35	46.90%	16,681,490 €	6,951 €	15392
4	45	40	59.18%	12,557,688 €	5,232 €	4563
5	50	45	99.16%	10,993,658 €	4,581 €	20

It was obtained a reliability outcome above 95% in configuration 5. Then it was attempted to find the configuration that fulfilled the minimum reliability requirement but with the lowest total cost possible. As for unimodal transport it is only necessary two entities (drivers and trucks), the possible combinations are way less than in intermodal where there are 5 entities. The procedure was to set a specific number of drivers and change the number of trucks until it is found the lowest total cost combination for each number of drivers set. In the table below are presented the configurations defined and respective results. When the increase of the number of trucks was originating more costs than benefits, the procedure was to change the number of drivers and try new combinations with trucks.

Table 16 - Unimodal configurations simulated (second batch)

Configuration	Unimodal Drivers	Trucks (PT)	**Reliability**	**Total Cost**	Cost/unit cargo	Late deliveries (days)
6	50	46	99.53%	11,010,329 €	4,588 €	11
7	50	47	99.74%	11,014,865 €	4,590 €	6
8	50	44	95.07%	11,011,159 €	4,588 €	125
9	50	43	80.47%	11,235,780 €	4,681 €	722
10	51	43	86.87%	11,121,240 €	4,634 €	402
11	51	44	96.09%	11,036,840 €	4,599 €	98
12	51	45	99.45%	11,012,335 €	4,588 €	13
13	51	46	99.78%	11,029,301 €	4,596 €	5
14	51	47	99.77%	11,050,310 €	4,604 €	6
15	49	44	88.66%	11,063,750 €	4,610 €	336
16	49	45	94.07%	11,010,535 €	4,588 €	151
17	**49**	**46**	**97.95%**	**10,978,655 €**	**4,574 €**	**51**
18	**49**	**47**	**99.18%**	**10,982,655 €**	**4,576 €**	**20**
19	48	46	90.58%	11,046,152 €	4,603 €	267
20	48	47	92.72%	11,030,431 €	4,596 €	185
21	48	48	96.77%	11,000,499 €	4,584 €	81
22	48	49	95.61%	11,023,168 €	4,593 €	111

To better visualise the results, Figure 35 contains a bar chart of the total cost of each configuration that outputted a reliability over 95%. The several bars colours correspond to the number of trucks in service for each configuration.

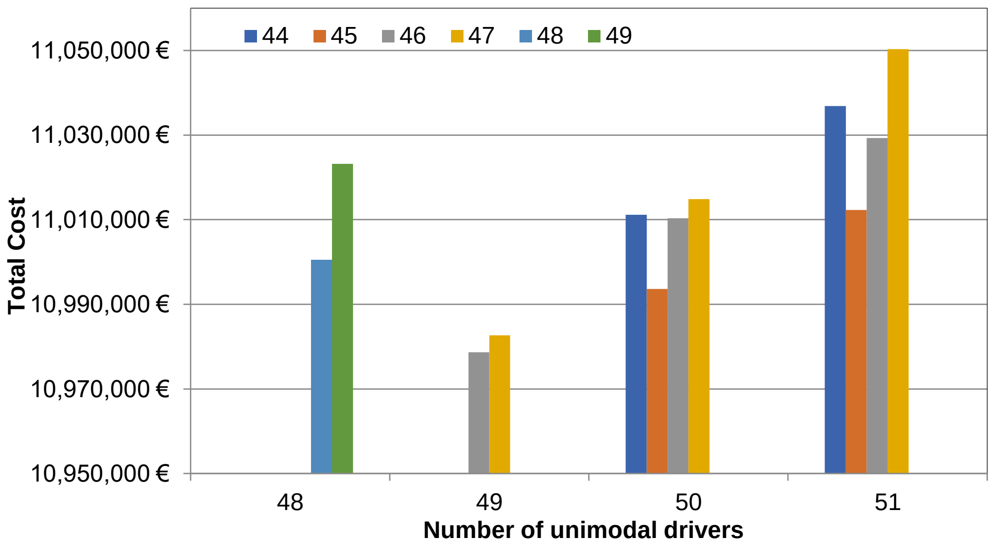


Figure 35 - Total cost of each configuration with over 95% of reliability

In Table 17 it is specified the total cost of each configuration but with the discarded combinations, highlighted in red.

Table 17 - Total cost of each configuration simulated (second batch)

Total Cost		Trucks (PT)						
		43	44	45	46	47	48	49
Unimodal Drivers	48	-			11,046,152 €	11,030,431 €	11,000,499 €	11,023,168 €
	49	-	11,063,750 €	11,010,535 €	**10,978,655 €**	**10,982,655 €**		
	50	11,235,178 €	11,011,159 €	10,993,658 €	11,010,329 €	11,014,865 €		
	51	11,121,724 €	11,036,840 €	11,012,335 €	11,029,301 €	11,050,310 €		

For each number of drivers there is an optimum number of trucks, that is, the output results correspond to the lower cost, making an efficient utilisation of both entities and balancing the investment with the penalties paid for late deliveries.

Analysing Figure 35 and Table 17, it gets clear that the best combination of drivers and trucks is found, but not obviously selected. The configurations that turn out the lowest total cost is configuration 17 with 10,978,655 €, contemplating 49 drivers and 46 trucks. Nevertheless, configuration 18 outputs a reliability 1.23% higher with a cost increment of 4,000 €, which corresponds to a 0.036% increase. It also displays a reduction in the days of late delivery from 51 to 20.

Both configurations 17 and 18 are good solutions for the problem approached, but since the reliability improvement that delivered by configuration 18 corresponds to such a tiny total cost increase, this was the configuration selected to better address the transport problem described.

The utilisation ratios in configuration over the year for both entities are present in Figure 36 and Figure 37.

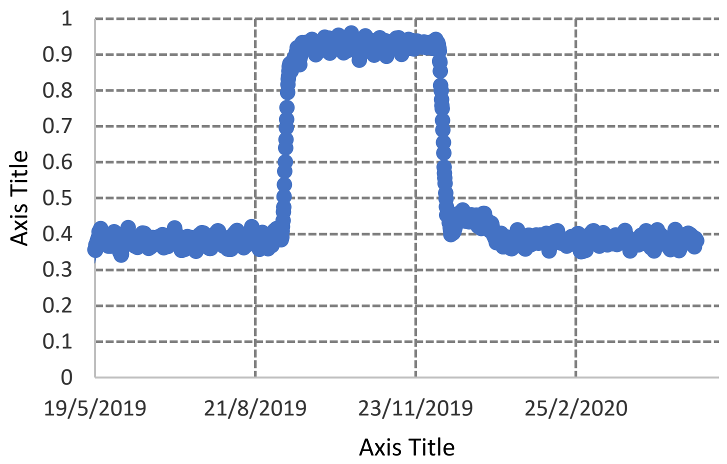


Figure 36 - Utilisation of trucks over the year (exclusive unimodal full road service)

It can be observed a jump in the utilisation for a finite period and this corresponds to the high season, when the demand for transportation increases drastically. The average utilisation of drivers during the high season does not reach the maximum, what could lead to think it should be reduced its quantity in order to maximize the utilisation. It is true, indeed, and the reduction of one truck, maintaining the number or drivers untouched, corresponds to configuration 17. As mentioned before, configuration 17 turns out to be slightly cheaper but damages reliability at a point that it is not considered advantageous, given the change in cost.

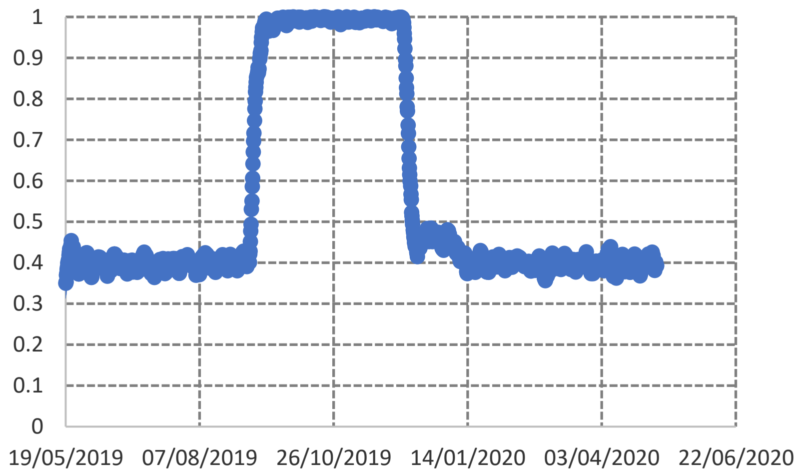


Figure 37 -Utilisation of drivers over the year (exclusive unimodal full road service)

Drivers utilisation turns out in full during the high season what leads to infer if it is in overutilisation, creating bottlenecks. If it is increased in one the number of drivers and keeping the number of trucks intact, it is created configuration 7. As it can be seen in Table 16, configuration 7 turns out more expensive than configuration 18, despite the slightly improvement in reliability.

6.2 Total cost

The cost structures have been specified in section 5.3 Internal costs calculation and were based on E. Tzannatos, S. Papadimitrious (2014) study, for an analogous transport service in Greece.

6.2.1 Intermodal

For the transport problem approached it is worthy of pointing out 7 of the configurations defined before. In the one hand, for being the configurations that conducted to the lowest total cost for each reliability level and in the other hand, these ones lead to some evidence regarding the influence of the choice of one transport solution over the other. In Figure 38 is represented the 30 intermodal configurations results of reliability and total cost, being stood out in orange the most interesting ones for a deeper analysis. Each point in the following figure correspond to an intermodal configuration.

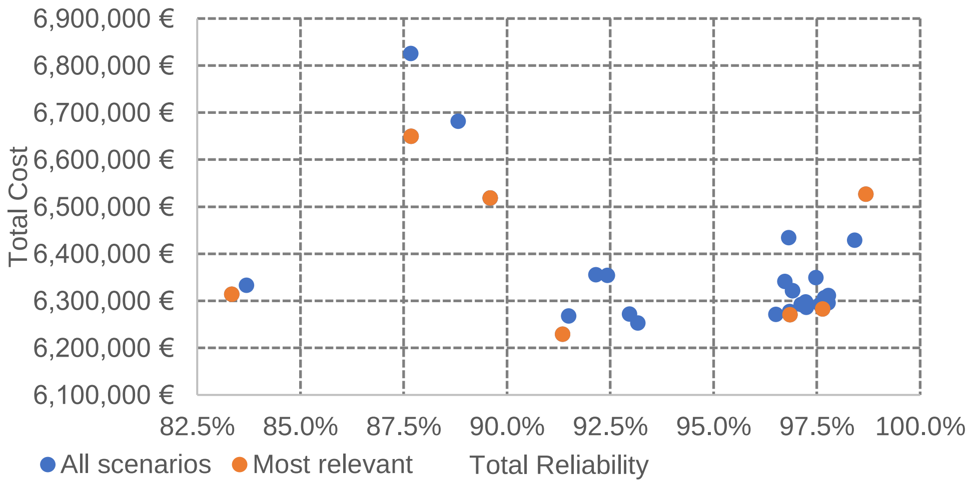


Figure 38 - Reliability and total costs of all intermodal configurations.

Since the number of late delivery days, reliability and total cost are interdependent, according to the following figure, it can be observed these three aspects together. The bars correspond to the total cost and in orange, the variation in the number of days of late delivery. The data is ordered by reliability, as in Table 18.

In Figure 39 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.

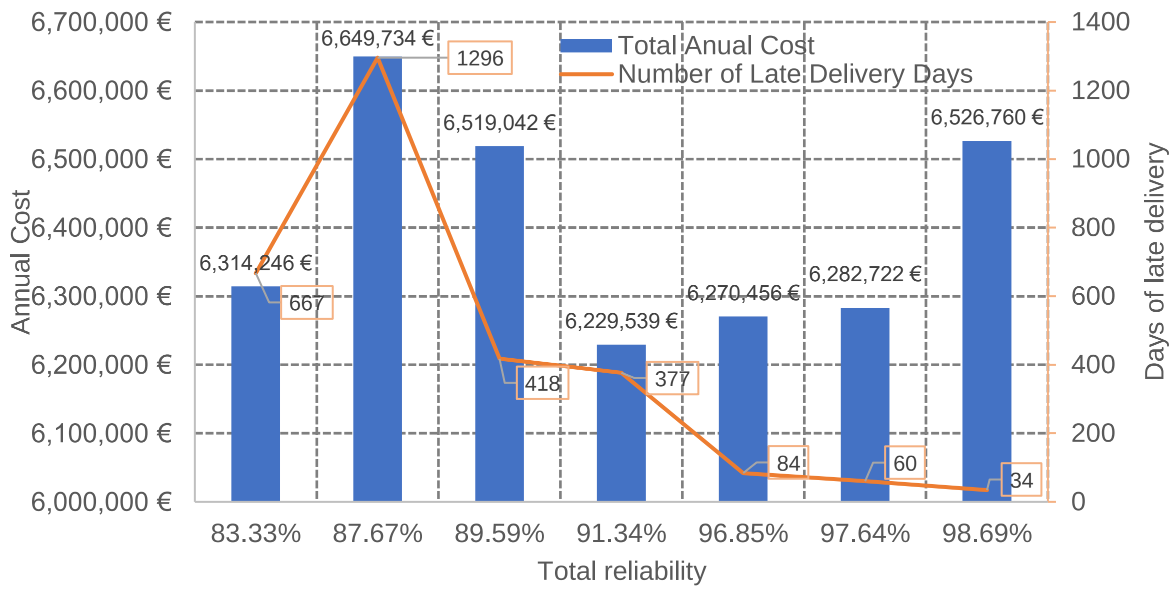


Figure 39 - Total cost, reliability, and days of late delivery of the intermodal configurations pointed out.

For each day of delivery delay, the logistic company pays a penalty to the customer of 400€ and by what is presented in the figure above, there is an inverse relation with reliability, except for one of the configurations represented. It was expectable that more days of delivery would lead to lower reliability results, although, it is not always a linear thought because one unsuccessful delivery does not mandatorily correspond to one day of late delivery and that is the explanation for the discrepancy in the first configuration represented in Figure 39, configuration 7. This discrepancy is possible to interpretate after analysing Table 18, where it is specified a few other outcomes that allow a better understanding of the relations between reliability and total cost and why the points in Figure 38 can be so spread out.

Table 18 shows, for these levels of reliability on an yearly basis, the size of the truck fleets in Portugal and France, the number of drivers in Portugal and in France, number of cargoes deviated to the road, number of intermodal cargoes that arrived within the delivery window, number of road cargoes that arrived within the delivery window, average utilisation of the truck fleets during the days before ship departure (during the 24 hours before the opening of the two days free time in the port of Leixões), average utilisation of the truck fleet in France during the 24 hours after ship arrival, average number of cargo units onboard the ship per week, total values of the penalties paid for late delivery (intermodal and road), total value of the transport costs for all the cargoes, average transit time Guimarães-Paris by road and by ship.

Table 18 – Further outputs of the most relevant intermodal configurations.

	Configurations						
	7	2	19	6	14	24	9
Intermodal Drivers PT	8	8	7	8	8	9	8
Unimodal Drivers	14	14	18	14	17	17	20
Intermodal Drivers FR	9	11	10	10	11	11	15
Trucks PT	16	15	19	16	18	18	20
Trucks FR	8	8	7	8	9	9	12
% Intermodal Share	77.6%	76.7%	74.4%	77.7%	77.4%	77.6%	77.3%
Intermodal Reliability	87.3%	97.7%	95.2%	96.7%	98.2%	98.5%	98.9%
Intermodal Cost [€]	3,538,198	3,457,494	3,324,100	3,482,554	3,492,790	3,526,299	3,642,264
% Unimodal Share	22.4%	23.3%	25.6%	22.3%	22.6%	22.4%	22.7%
Unimodal Reliability	69.5%	54.5%	73.3%	72.9%	92.2%	94.7%	98.0%
Unimodal Cost [€]	2,776,048	3,192,240	3,194,942	2,746,984	2,777,666	2,756,424	2,884,495
Total Reliability	83.3%	87.7%	89.6%	91.3%	96.8%	97.6%	98.7%
High season utilisation of trucks PT 72h before ship departure	0.83	0.89	0.80	0.82	0.69	0.67	0.55
High season utilisation of trucks FR 24h after ship arrival	0.88	0.94	0.95	0.93	0.92	0.91	0.84
Average Number or Cargoes Onboard per week	36	35	34	36	36	36	36
Total late delivery penalties [Unimodal]	375	1252	324	313	50	31	12
Total late delivery penalties [Intermodal]	292	44	93	64	34	29	22
Total transport costs [€]	6,314,246	6,649,734	6,519,042	6,229,539	6,270,456	6,282,722	6,526,760
Average transit time Guimarães-Paris [Intermodal]	183 h	175 h	178 h	178 h	174 h	174 h	172 h
Minimum transit time Guimarães-Paris [Intermodal]	91 h	91 h	91 h	90 h	92 h	91 h	92 h
Average transit time Guimarães-Paris [Unimodal]	63 h	106 h	60 h	60 h	44 h	41 h	38 h
Minimum transit time Guimarães-Paris [Unimodal]	33 h	33 h	33 h	33 h	33 h	33 h	33 h

Configurations 6 and 7 only differ in the number of intermodal driver based in France, what made a big difference. In configuration 7 happened that the reliability of intermodal service was the lowest of the configurations pointed out above. This lowered the total reliability considerably since the number of shipped cargoes via intermodal is three times bigger that via unimodal. Also, intermodal service delivered cargoes 4 days delayed at maximum and unimodal service reaches the 8 days of delay. Despite the number of penalties applied to both services is close to each other, the number of delayed cargoes via intermodal is way bigger, what lowered the total reliability.

The total cost of both configurations 6 and 7 are close to each other, although reliability is much different, since the bottleneck created in configuration 6 by intermodal drivers based in France delayed the delivery of numerous cargoes, what increased the costs due to the penalties payed, despite the saving in the salary of one driver.

The conditions of configuration 2 and configuration 6 are not much different either, although, the lower quantity of trucks based in Portugal in configuration 2 caused a problem in shipping unimodal cargoes, since intermodal service has preference when the system has to allocate the resources/entities. This increased severely the number of penalties for late delivery but did not damaged the total reliability as much as the delays from the intermodal service in configuration 7, for the reasons supra-mentioned. In configuration 2, it is reached 18 days of delay from unimodal service, what creates big expenses but since it is not shipped so much cargoes via unimodal, the total reliability is not so prejudiced.

Configurations 6 and 19 outputted not much different reliability results, although in configuration 19, intermodal service was jeopardized, causing an increase of cargoes shipped via unimodal (unimodal share). The individual services reliabilities are approximate but unimodal service leads to higher costs since it uses for longer a driver and a truck to ship a cargo unit, despite not having subcontract maritime transport.

As it could be rapidly seen in Figure 39, configuration 6 it the one computing a lower total cost, but unfortunately it does not fulfil the reliability minimum requirement of 95% and consequently, it could not be considered as a possible solution for the transport problem approached. Hence, it was necessary to increase the number of entities in order to increase reliability.

Configuration 14, as concluded before in 6.1.1 Intermodal, is 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 penalties. Configurations 9 and 24 are examples of that, 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 24 hours after ship arrival is very high (close to 1), as observed in the utilisation plots in page 57 for configuration 14, but also for all the highlighted configurations in Table 18. This indicates a very efficient use of those entities.

The 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.

In the following table it is specified the internal costs of each configuration, separated by fixed and variables costs. The fixed costs are directly proportional to the number of resources (trucks and drivers) and so, lower quantities of resources correspond to lower fixed costs. Tolling, fuel, lubricant, and tire replacement costs are very representative in the unimodal solution, since it uses much more the truck. On the other hand, the intermodal solution has the significant extra cost of ship transportation, although it turns out cheaper when compared with the unimodal one.

Table 19 - Detailed internal costs of the two modalities considered.

			Configurations						
			7	**2**	**19**	**6**	**14**	**24**	**9**
Intermodal	**Fixed Costs [€]**	**annualised capital investment**	79,729	77,951	72,392	79,728	89,299	89,057	114,645
		driver's annual cost	429,828	480,396	429,828	455,112	480,396	505,680	581,532
		Other fixed costs	69,361	67,814	62,977	69,359	77,686	77,475	99,736
		maintenance	20,430	19,975	18,550	20,430	22,883	22,820	29,377
	Variable Costs [€]	**Tolling PT**	51,057	50,779	49,036	51,373	50,968	51,133	50,771
		Tolling FR	256,305	253,485	246,110	257,465	255,680	256,308	255,142
		Fuel	839,346	830,363	802,113	842,259	833,096	837,688	834,403
		Lubricants	149,883	148,279	143,235	150,403	148,767	149,587	149,000
		Tire replacement	149,883	148,279	143,235	150,403	148,767	149,587	149,000
		Ship Transport	1,375,575	1,362,713	1,319,325	1,380,563	1,371,788	1,375,463	1,369,838
		Late delivery fines	116,800	17,460	37,300	25,460	13,460	11,500	8,820
Unimodal	**Fixed Costs [€]**	**annualised capital investment**	107,591	101,564	130,538	107,592	121,436	121,678	135,115
		driver's annual cost	420,000	420,000	540,000	420,000	510,000	510,000	600,000
		Other fixed costs	93,599	88,356	113,563	93,601	105,644	105,855	117,544
		maintenance	27,570	26,025	33,450	27,570	31,117	31,180	34,623
	Variable Costs [€]	**Tolling Portugal**	19,935	20,737	22,685	19,884	20,079	19,883	20,120
		Tolling Spain	33,964	35,315	38,683	33,903	34,233	33,935	34,274
		Tolling France	214,016	222,647	243,035	213,500	214,929	213,783	215,250
		Fuel	1,259,435	1,309,116	1,431,897	1,256,842	1,267,434	1,258,181	1,269,350
		Lubricants	224,899	233,771	255,696	224436	226,327	224,675	226,670
		Tire replacement	224,899	233,771	255,696	224436	226,327	224,675	226,670
		Late delivery fines	150,140	500,940	129,700	125,220	20,140	12,580	4,880
Total Annual Cost [€]			**6,314,246**	**6,649 734**	**6,519,042**	**6,229,539**	**6,270,456**	**6,282,722**	**6,526,760**

6.2.2 Unimodal

The configurations defined to test unimodal exclusive solution were presented in section 6.1.2 Unimodal and Figure 40 it is represented the distribution of all configurations regarding their total reliability and cost.

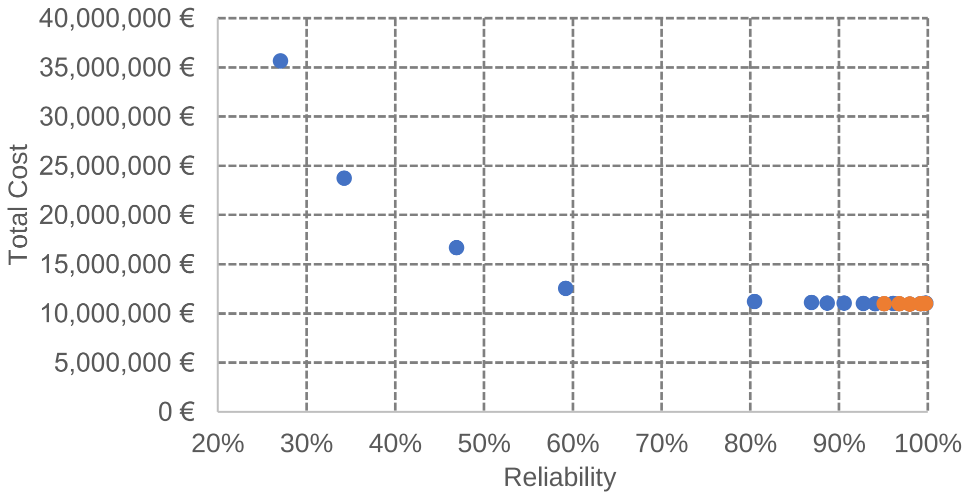


Figure 40 - Reliability and total costs of all unimodal configurations.

As there are only two entities as variables, the relation between cost and reliability it is a lot easier to define as a function, for example, since the outputs are much less dispersed.

The configurations that outputted a reliability under 95% cannot be considered and the remaining ones are represented in Figure 41. It was selected 5 intermodal configurations for a deeper analysis, having for that the same criteria as in the previous section, for intermodal: Configurations that both have the lowest cost for each reliability level and lead to the most relevant considerations over the solutions found for the transport problem approached. These configurations are marked in orange in the following figure.

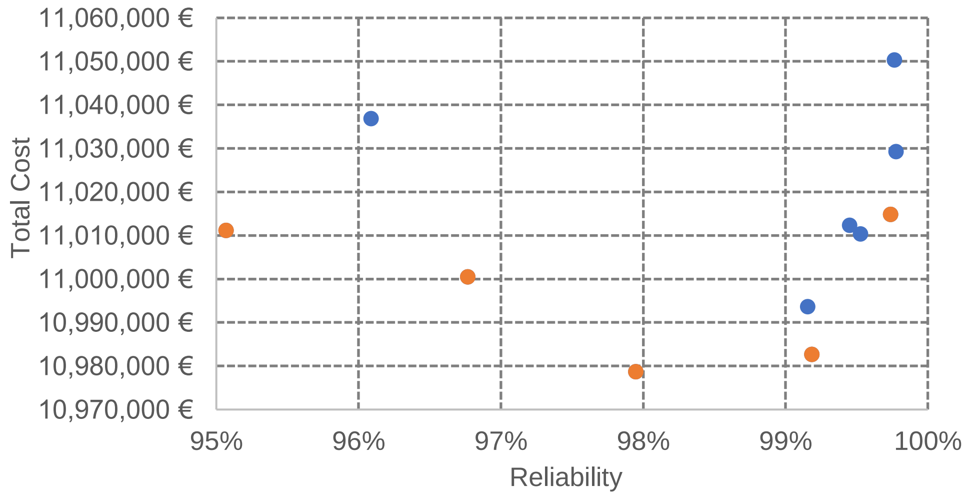


Figure 41 - Reliability and total costs of all unimodal configurations with a reliability outcome over 95%.

As mentioned before, it is applied a penalty to the logistic company for each day of delivery delay, regardless of the transport solution chosen. In Figure 42 it can be observed the relation between the number of penalties applied, total cost and total reliability. The data is ordered by reliability and not by configuration number.

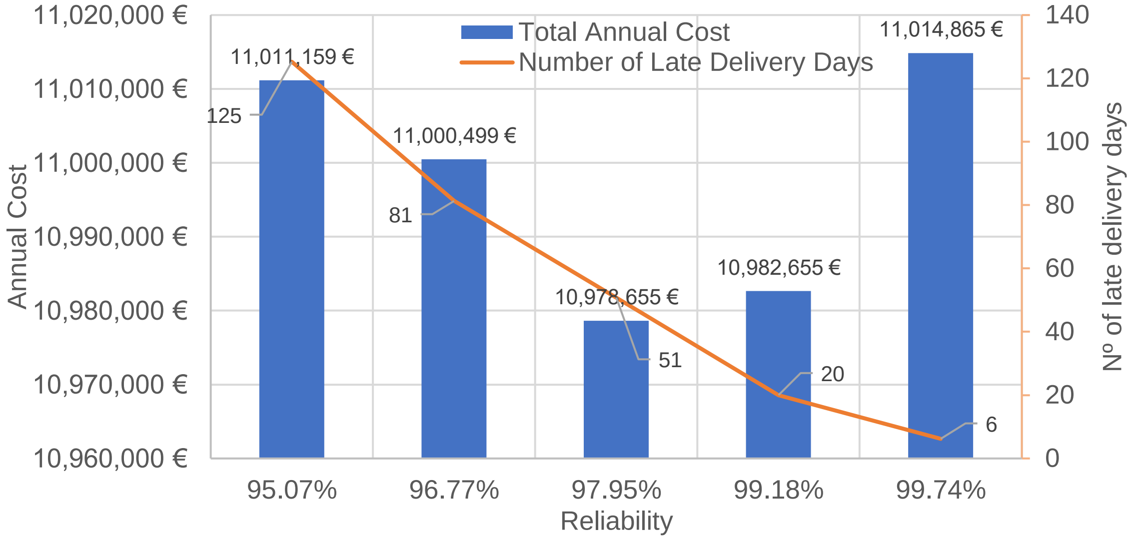


Figure 42 - Total cost, reliability, and days of late delivery of the unimodal configurations pointed out.

It can be found in Table 20, other relevant results for the configurations highlighted, allowing to understand better the behaviour of the system under the different conditions.

Table 20 - Further outputs of the most relevant unimodal configurations.

	Configurations				
	8	**21**	**17**	**18**	**7**
Unimodal Drivers	50	48	49	49	50
Trucks PT	44	48	46	47	47
Reliability	95.1%	96.8%	97.9%	99.2%	99.7%
Total Cost [€]	11,011,159	11,000,499	10,978,655	10,982,655	11,014,865
High season utilisation of drivers	0.93	0.97	0.96	0.96	0.95
High season utilisation of trucks	0.95	0.87	0.91	0.90	0.91
Total late delivery penalties	125	81	51	20	6
Average transit time Guimarães-Paris	47 h	46 h	44 h	43 h	40 h
Minimum transit time Guimarães-Paris	33 h	33 h	33 h	33 h	33 h

It was already clear, by analysing Figure 35 from page 61, that 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.

Similar to Table 19 for intermodal transport, in the following table is specified the internal costs of each configuration, separated by fixed and variables costs.

Table 21 - Detailed internal costs of the full road exclusive transport solution.

			Configurations				
			8	21	17	18	7
Unimodal	Fixed Costs [€]	Annualised capital investment	343,420	374,640	359,030	366,835	366,835
		Driver's annual cost	1,500,000	1,440,000	1,470,000	1,470,000	1,500,000
		Other fixed costs	298,760	325,920	312,340	319,130	319,130
		maintenance	88,000	96,000	92,000	94,000	94,000
	Variable Costs [€]	Tolling Portugal	88,678	88,766	88,687	88,614	88,831
		Tolling Spain	151,605	151,538	151,525	151,490	151,570
		Tolling France	939,216	939,371	938,181	938,194	939,519
		Fuel	5,564,174	5,564,443	5,560,632	5,560,500	5,565,001
		Lubricants	993,603	993,651	992,970	992,946	993,750
		Tire replacement	993,603	993,651	992,970	992,946	993,750
		Late delivery fines	50,100	32,520	20,320	8,000	2,480
Total Annual Cost [€]			**11,011,159**	**11,000,499**	**10,978,655**	**10,982,655**	**11,014,865**

6.3 Discussion

From the point of view of the logistic company, when a trailer is shipped via intermodal it is considered the return to Portugal without representing a cost for the company. To maximize profits, it is usual to wait for a booking from a close origin to Portugal to have the trailer back, since its value and respective depreciation are not substantial. When using the fully road-based transportation, it is attempted to do the same with trucks and drivers but many times there is not a transportation demand close to the time of arrival to France. Since trucks and drivers are expensive assets, they cannot wait long for a booking due to the corresponding waiting costs (drivers' hourly rate, truck depreciation, etc). This sometimes makes both trucks and drivers return not monetizing the voyage.

This assumption difference between the unimodal and intermodal solutions does not allow an even comparison between each other, thus, to better understand the differences between the two system configurations, it was taken into consideration the cost of the semi-trailer return voyage. If it is shipped by intermodal it is assumed to return via intermodal as well.

It was selected one configuration from each system configuration, with approximately the same overall reliability (over 95%). The intermodal one is the most advantageous configuration found, number 14, and it was selected the unimodal one with approximately the same reliability output, configuration number 21.

To split proportionally the fixed costs related with trucks based in Portugal, between the two components (unimodal and intermodal), it was measured the utilisation time of trucks by each component. The intermodal and unimodal services use these trucks averagely for 3h34 and 78h (including mandatory periodical rests) for each cargo transported. The trucks based in France are only used by the intermodal service thus, its costs were only considered for the intermodal component.

In Table 22 it is presented the fixed and variable costs obtained for each configuration.

Table 22 - Costs of intermodal and unimodal configurations with the same reliability output.

		Intermodal configuration 14		**Unimodal Configuration 21**
		Intermodal component	Unimodal component	Unimodal component
Fixed costs	**Annualised capital investment**	89,299 €	121,436 €	374,640 €
	Driver's annual cost	480,396 €	510,000 €	1,440,000 €
	Other fixed costs	77,686 €	105,644 €	325,920 €
	Maintenance	22,883 €	31,117 €	96,000 €
Variable costs	**Tolls**	306,648 €	269,241 €	1,179,675 €
	Fuel, lubricants, and tires replacement	1,130,631 €	1,720,089 €	7,551,744 €
	Ship transport	2,743,575 €	-	-
	Late delivery penalties	13,460 €	20,140 €	32,520 €
Total transport costs		7,642,244 €		11,000,499 €

It is notorious the difference in the fixed costs between the two configurations. The unimodal transportation requires much more resources due higher utilisation time for each cargo transported. Also, the distances travelled by road are approximately 10 times bigger than in intermodal transportation. Hence, the variable costs related with tolls, fuel, lubricants, and tire replacement are substantially higher as well in the unimodal components. These variable costs turn out to be the most relevant costs in the whole unimodal cost structure, making this solution so much more expensive.

The late delivery penalties are approximately the same, since the reliability is as well, what indicates that the cargoes delivered outside time window arrived approximately the same days late. This can be verified by analysing Table 23. The time range considered regards only the time after the scheduled delivery and since the time window is of 48h, it is not applied penalties for cargoes delivered in this interval.

Table 23 - Deliveries dispersion over time in both intermodal and unimodal configurations with the same reliability output.

		Intermodal configuration 14				**Unimodal configuration 21**	
		Intermodal		**Unimodal**			
Time Range [h]		**Deliveries**	**Penalties**	**Deliveries**	**Penalties**	**Deliveries**	**Penalties**
0	24	1393	-	431	-	1830	-
24	48	431	-	70	-	492	-
48	72	32	32	35	35	73	73
72	96	1	2	7	14	5	10
96	120	0	-	0	-	0	-

In both configurations, the delivery dispersion over time is very similar. If a cargo arrives from 48 hours to 72 hours after scheduled, it is one day out of time window, what implies one late delivery penalty. If it is delivered from 72 hours to 96 hours after scheduled, it is two days out of time window, implying then two late delivery penalties.

In the following table, it is presented several performance indicators measured that allow a further comprehensive interpretation of the results.

Table 24 - Performance indicators of intermodal and unimodal configurations with the same reliability output.

	Intermodal configuration 14		**Unimodal Configuration 21**
	Intermodal component	Unimodal component	Unimodal component
Share (%)	77.4%	22.6%	-
Reliability	98.2%	92.2%	-
Cost	4,864,578 €	2,777,666 €	-
Cargo transported	1,857	543	2,400
Cost/cargo transported	2,619 €	5,117 €	4,584 €
Total transport costs	7,642,244 €		11,000,499 €
Total Reliability	96.8%		96.8%
Total late delivery penalties	34	50	81
Deliveries in the first 24h (within time window)	75.0%	79.3%	76.3%
Deliveries 24h to 48h after scheduled (within time window)	23.2%	12.8%	20.5%
Deliveries 1 day after time window	1.7%	6.4%	3.0%
Deliveries 2+ days after time window	0.1%	1.4%	0.2%
Average transit time Guimarães-Paris	174 h	44 h	46 h
Minimum transit time Guimarães-Paris	92 h	33 h	33 h

As shown before in Table 18, the intermodal share is the triple of the unimodal, what makes of utter importance to keep a high level of reliability of this component since it transports most of the cargo. Considering the impact that the road variable costs have in the transport cost, the company benefits by using the intermodal solution, even considering the cost of return of the trailer. The cost per cargo transported is the double via road transport than via intermodal.

In terms of dispersion of the deliveries, the intermodal configuration shows better results in the intermodal components since the percentage of cargoes delivered outside time window is lower. Although in the unimodal configuration, this percentage is much lower than in the unimodal component of the intermodal configuration. Since both configurations have the same total reliability, it can be concluded that the lower performance of the unimodal component of the intermodal configuration is due to the intermodal configuration priority in the use of the resources, namely, the trucks based in Portugal. If there were enough resources for the unimodal component, its reliability would certainly be higher than the intermodal component. That is verified in the conditions of the intermodal configuration number 9 (the one that outputted the highest reliability output, in both components), as shown in Table 25.

Table 25 - Deliveries dispersion over time in the intermodal configuration with the highest reliability output.

		Intermodal configuration 9			
		Intermodal		Unimodal	
Time [h]		Deliveries	Penalties	Deliveries	Penalties
0	24	1527	-	490	-
24	48	309	-	50	-
48	72	19	19	2	9
72	96	1	2	1	2
96	120	0	-	0	-

The unimodal component, having enough resources (trucks and drivers) to satisfy its demand for transportation, outputs higher reliability than the intermodal one. The cargoes delivered outside the time window were of 0.63% and 1.11% for unimodal and intermodal components, respectively. This result supports, in part, the preference for road transport over intermodal, in the real world.

6.3.1 Sensitivity Analysis

To evaluate the impact, the change in quantity of each resource has in the selected intermodal and unimodal configurations, the model was simulated for each combination of resources.

The intermodal configuration number 14 was found as the most advantageous configuration, thus, it was taken as basis for the sensitivity analysis presented next. As the intermodal system has too many types of resources, to combine the changes in resources would require too many simulations to evaluate all possible configurations, hence, the change in resources was done separately.

In Table 26 is presented the change in reliability when varying the number of each resource of the intermodal configuration 14.

Table 26 – Total reliability change when varying the number of each resource separately in the intermodal configuration.

Change in resources	Intermodal Drivers (PT)	Unimodal Drivers	Intermodal Drivers (FR)	Trucks (PT)	Trucks (FR)
-2	-17.38%	-3.95%	-2.60%	-7.83%	-4.01%
-1	-8.29%	-1.97%	-0.39%	-3.15%	-0.35%
0	0.00%	0.00%	0.00%	0.00%	0.00%
1	0.82%	0.05%	0.06%	0.41%	0.39%

In Table 27 it is presented the change in the total cost when varying the number of each resource of the intermodal configuration 14.

Table 27 - Total cost change when varying the number of each resource separately in the intermodal configuration.

Change in resources	Intermodal Drivers (PT)	Unimodal Drivers	Intermodal Drivers (FR)	Trucks (PT)	Trucks (FR)
-2	39.60%	-0.25%	-0.17%	6.80%	0.02%
-1	6.56%	-0.55%	-0.11%	2.00%	0.01%
0	0.00%	0.00%	0.00%	0.00%	0.00%
1	0.20%	1.13%	0.82%	0.25%	0.44%

As it can be verified by analysing Table 26 and Table 27, there is not a configuration that can increase the reliability without increasing the total cost as well. This also supports the conclusion taken before that stands configuration 14 as the best solution for the problem described.

The only change in the resource quantities that could lower the total cost is the reduction in one of the unimodal drivers, although, the loss in reliability does not make up, falling under 95%. On the other hand, the change that increases reliability for the lowest cost increase is the increment of one intermodal driver based in Portugal. This would increase reliability in 0.82% (the highest obtained) for a increase of 0,2% (the lowest when increasing quantities of any resource).

The unimodal configuration number 21 was found as the most advantageous configuration. Thus, it was taken as basis for the sensitivity analysis of the unimodal solution. As the unimodal configurations have only two types of resources, it as simulated every configuration of the combined number or resources. In Table 28 it is presented the change in reliability when varying the number of each resource of the unimodal modal configuration number 21.

Table 28 - Total reliability change when varying the number of resources in the unimodal configuration.

Change in reliability		Trucks (PT)						
		-4	-3	-2	-1	0	+1	+2
Unimodal Drivers	-1	-	-	-	-8.68%	-6.52%	-2.44%	-3.60%
	0	-	-10.61%	-5.15%	-1.25%	**0.00%**	-	-
	+1	-18.87%	-4.15%	-0.03%	0.35%	0.56%	-	-
	+2	-12.42%	-3.12%	0.27%	0.60%	0.59%	-	-

In Table 29 is presented the change in the total cost when varying the number of each resource of the unimodal modal configuration number 21.

Table 29 - Total cost change when varying the number of resources in the unimodal configuration.

Change in total cost		Trucks (PT)						
		-4	-3	-2	-1	0	+1	+2
Unimodal Drivers	-1	-	-	-	0.58%	0.44%	0.16%	0.37%
	0	-	0.74%	0.25%	-0.04%	**0.00%**	-	-
	+1	2.30%	0.26%	0.10%	0.25%	0.29%	-	-
	+2	1.27%	0.49%	0.27%	0.42%	0.62%	-	-

By analysing Table 28 and Table 29, it is only verified a tiny decrease in the total cost when decreasing a unit in the number of trucks, although the loss in reliability is much more significative than this reduction in cost, what turns this configuration not so advantageous, as approached before in section 0. In the other hand, the change that increases reliability for the lowest cost increase is the increment of one driver. This would increase reliability in 0.56% for a increase of 0.29%.

In sum, the system that can reach the higher reliability results, regardless of the cost associated, is the unimodal. The intermodal system is affected by more uncertainties, thus decreasing the reliability. Nevertheless, both reach high reliability results and a performance over 95% is widely accepted in the market. So, intermodal transportation turns out as the most economically attractive solution, since for the same reliability results, the cost can be 30% cheaper than the unimodal homologous.

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 purpose of the simulation is to quantify the reliability of each transport solution, separately and combined, when the sizes of the truck fleets and the number of drivers both in Portugal and France are modified. It is studied the transport solution where it is used both intermodal transportation and unimodal (full road) when the first is not expected to deliver cargo meeting the delivery time window set for each cargo and the transport solution where it is used exclusively unimodal transportation. Both 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.

The main uncertainties regarding the two transport solutions have been included in the simulation models and affect the behaviour of the systems. The demand for transportation over a period of one year is fixed for a variety of pairs origin-destination but the time of occurrence of customer bookings is however uncertain and affected by seasonality effects, namely in Autumn, when world demand increases. Also, the time to deliver each cargo is uncertain. Regarding the maritime transportation, the availability of cargo space in the ship and ship departure time are uncertain as well as the ship technical off-hire, port strikes or bad weather events, that delays the ship for 24h per occurrence. Roads located in Northern France are affected by the bad weather events, causing its closure for 24h as well. At last, the road and ship velocities follow random distributions, creating uncertainties regarding this aspect too.

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%. The resources used to obtain such result were for a fleet of 18 trucks in Portugal (used for both unimodal and intermodal transport) and 9 trucks in France. Truck drivers need to number 8 for intermodal transport in Portugal, 17 for unimodal transport and 11 for intermodal transport in France.

This corresponded to 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 full unimodal transportation, under the assumptions of the current model, the minimum total cost of the system occurred under conditions that outputted a reliability of 99.18%, which easily fulfils the reliability level requirement. The conditions that leaded to this reliability result were for a fleet of 47 trucks in Portugal and 49 drivers. This corresponds 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 a consequence.

Comparably to 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 the control of a logistic company and cannot even be predicted, such as technical off hires, strikes, road closures due to bad weather, etc.

It is worth pointing out that the costs of the unimodal exclusive solution consider the return voyage to Portugal, not considering a potential service on the way back to monetize the trip. On the other hand, the intermodal solution considers that the maritime transport is subcontracted, not having to deal with the costs of the return voyage nor the logistics of recovering the trailer. Although, to compare the two transport solutions, intermodal and unimodal (fully road-based), it was recalculated the total cost considering the costs of the trailer return voyage. This way, both transport solutions were under the same conditions and it was obtained a clear economical advantage of about 30% using the intermodal solution.

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.

REFERENCES

ALTIOK, T., MELAMED, B. (2007). **Simulation modeling and analysis with Arena**. First ed. London: Elsevier.

BANKS, J. (1998). **Handbook of Simulation: Principles, Methodology, Advances, Applications, and Practice**. New York, USA: Wiley-Interscience.

BANKS, J., II, J., NELSON, B., NICOL, D. (2009). **Discrete-event System Simulation**. Pearson; 5th Edition.

CARIS, A., MACHARIS, C., JANSSENS, G. K., (2008). Planning problems in intermodal freight transport: Accomplishments and prospects. **Transportation Planning and Technology**, v. 31, n. 3, p. 277–302.

CRAINIC, T. G., PERBOLI, G., ROSANO, M., (2017). Simulation of intermodal freight transportation systems: a taxonomy. **European Journal of Operational Research**, v. 270, n. 2, p. 401–418.

DEMIR, E., BURGHOLZER, W., HRUŠOVSKÝ, M., ET AL., (2016). A green intermodal service network design problem with travel time uncertainty. **Transportation Research Part B: Methodological**, v. 93, p. 789–807.

E. TZANNATOS, S. PAPADIMITRIOUS, A. K., (2014). The cost of modal shift : a short sea shipping service compared to its road alternative in Greece. , , n. October 2015, p. 1–20.

ERFURTH, T., BENDUL, J., (2017). Transportation time and reliability in intermodal transport chains. **International Journal of Transport Economics**, v. 44, n. 2, p. 257–271.

EUROPEAN COMMISSION, (2011). Transport White Paper: Roadmap to a Single European Transport Area – Towards a Competitive and Resource Efficient Transport System. , p. 31.

EUROPEAN COMMISSION. (2019). **Statistical Pocketbook 2019: EU transport**. Publications Office of the European Union.

EUROPEAN PARLIAMENT AND COUNCIL, (2006). Regulation (EC) No 561/2006. **Official Journal of the European Union**, v. L 102, p. 1–13. Available in: <http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02006R0561-20150302&from=EN>.

EUROSTAT. (2017). **Statistical pocketbook 2017**. .

FLODÉN, J. (2007). **Modelling Intermodal Freight Transport - The Potential of Combined Transport in Sweden**. .

GOOGLE (1), [Google Maps directions to drive from the multiple origins in Portugal to the multiple destinations in Northern France]. Retrieved August 6, 2019, as from https://goo.gl/maps/MBzVj4MGXmTaMbmW9. .

GROOTHEDDE, B., RUIJGROK, C., TAVASSZY, L., (2005). Towards collaborative, intermodal hub networks. A case study in the fast moving consumer goods market. **Transportation Research Part E: Logistics and Transportation Review**, v. 41, n. 6 SPEC. ISS., p. 567–583.

HANAOKA, S., REGMI, M. B., (2011). Promoting intermodal freight transport through the development of dry ports in Asia: An environmental perspective. **IATSS Research**, v. 35, n. 1, p. 16–23.

HRUŠOVSKÝ, M., DEMIR, E., JAMMERNEGG, W., VAN WOENSEL, T., (2016). Hybrid simulation and optimization approach for green intermodal transportation problem with travel time uncertainty. **Flexible Services and Manufacturing Journal**, v. 30, n. 3, p. 486–516.

JANIC, M., (2007). Modelling the full costs of an intermodal and road freight transport network. **Transportation Research Part D: Transport and Environment**, v. 12, n. 1, p. 33–44.

JEMAI, J., ZEKRI, M., MELLOULI, K., (2012). An NSGA-II algorithm for the green vehicle routing problem. **Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)**, v. 7245 LNCS, p. 37–48.

JENSEN, A. (1990). **Combined Transport: Systems, Economics and Strategies**. Swedish Transport Research Board.

JENSEN, A., (2008). Designing intermodal transport systems: A conceptual and methodological framework. **The Future of Intermodal Freight Transport: Operations, Design and Policy**, , n. March, p. 187–205.

KELLE, P., JIN, M., (2016). A Simulation Model for Intermodal Freight Transportation in Louisiana March 2016 LTRC Project Number : 14-2SS State Project Number : 30001395 Peter Kelle and Mingzhou Jin Department of Information Systems and Decision Sciences , National Center for Interm. , , n. 2.

KELTON, W. D., LAW, A. (2000). **Simulation modeling and analysis**. Boston, USA: McGraw-Hill Education.

LEHMAN, R. S. (1977). **Computer Simulation and Modeling: An Introduction**. Hillsdale, N.J.: Erlbaum.

LI, L., NEGENBORN, R. R., DE SCHUTTER, B., (2015). Intermodal freight transport planning - A receding horizon control approach. **Transportation Research Part C: Emerging Technologies**, v. 60, p. 77–95.

MACHARIS, C., BONTEKONING, Y. M., (2004). Opportunities for OR in intermodal freight transport research: A review. **European Journal of Operational Research**, v. 153, n. 2, p. 400–416.

MACHARIS, C., GEURS, K. T., (2019). The future of European communication and transportation research: A research agenda. **Region**, v. 6, n. 3, p. D1–D21.

MATTEI, G., BARNI, A., CANNATA, M., ET AL., (2015). Criteria Analysis of Intermodal Transport Networks. .

NUZZOLO, A., COPPOLA, P., COMI, A., (2013). FREIGHT TRANSPORT MODELING: REVIEW AND FUTURE CHALLENGES. **International Journal of Transport Economics**, v. 40(2), p. 151–181.

PREUSSER, M. M., (2008). A combined approach of simulation and optimization in supply chain management. , , n. April, p. 1–142. Available in: <http://othes.univie.ac.at/605/>.

QUADE, E. S. (1980). **Pitfalls of Analysis**. Chichester, UK: John Wiley & Sons.

REIS, V., (2014). Analysis of mode choice variables in short-distance intermodal freight transport using an agent-based model. **Transportation Research Part A: Policy and Practice**, v. 61, p. 100–120. Elsevier Ltd. Available in: <http://dx.doi.org/10.1016/j.tra.2014.01.002>.

REIS, V., MACÁRIO, R., (2008). Fitness: An agent based modelling approach to freight intermodal chains. .

ROSO, V., WOXENIUS, J., LUMSDEN, K., (2009). The dry port concept: connecting container seaports with the hinterland. **Journal of Transport Geography**, v. 17, n. 5, p. 338–345. Elsevier Ltd. Available in: <http://dx.doi.org/10.1016/j.jtrangeo.2008.10.008>.

SAMBRACOS, E., MANIATI, M., (2012). Competitiveness between short sea shipping and road freight transport in mainland port connections; the case of two Greek ports. **Maritime Policy and Management**, v. 39, n. 3, p. 321–337.

SANTOS, T. A., ESCABELADO, J., BOTTER, R., SOARES, C. G., (2020). Simulating Ro-Ro operations in the context of supply chains. **Short Sea Shipping in the Age of Sustainable Development and Information Technology**. 1st ed, p.25. Routledge.

SANTOS, T. A., GUEDES SOARES, C., (2017a). Modeling of Transportation Demand in Short Sea Shipping. **Maritime Economics and Logistics**, v. 19, n. 4, p. 695–722.

SANTOS, T. A., GUEDES SOARES, C., (2017b). Ship and fleet sizing in short sea shipping. **Maritime Policy and Management**, v. 47, n. 7, p. 859–881.

SANTOS, T. A., MARTINS, P., SOARES, C. G., (2019). Short sea shipping and the promotion of multimodality in the European Atlantic Area. , p. 1–27.

SANTOS, T. A., SOARES, C. G., BOTTER, R. C., (2018). Characterizing the Operation of a Roll-on Roll-off Short Sea Shipping Service. **Progress in Maritime Engineering and Technology**. p.77–88. Taylor & Francis Group, London.

SONG, M., YIN, M., CHEN, X. (MICHAEL), ZHANG, L., LI, M., (2013). A Simulation-based Approach for Sustainable Transportation Systems Evaluation and Optimization: Theory, Systematic Framework and Applications. **Procedia - Social and Behavioral Sciences**, v. 96, n. Cictp, p. 2274–2286. Elsevier B.V. Available in: <http://dx.doi.org/10.1016/j.sbspro.2013.08.257>.

SOUTHWORTH, F., PETERSON, B. E., (2000). Intermodal and international freight network modeling. **Transportation Research Part C: Emerging Technologies**, v. 8, n. 1–6, p. 147–166.

STEADIESEIFI, M., DELLAERT, N. P., NUIJTEN, W., VAN WOENSEL, T., RAOUFI, R., (2014). Multimodal freight transportation planning: A literature review. **European Journal of Operational Research**, v. 233, n. 1, p. 1–15. Elsevier B.V. Available in: <http://dx.doi.org/10.1016/j.ejor.2013.06.055>.

STINGĂ, V. G., (2017). Analysis regarding the transport network models. Case study on finding the optimal transport route. **IOP Conference Series: Materials Science and Engineering**, v. 227, n. 1.

TAWFIK, C., LIMBOURG, S., (2018). Pricing problems in intermodal freight transport: Research overview and prospects. **Sustainability (Switzerland)**, v. 10, n. 9.

TAWFIK, C., LIMBOURG, S., (2019). Scenario-based analysis for intermodal transport in the context of service network design models. **Transportation Research Interdisciplinary Perspectives**, v. 2, n. October, p. 100036. The Authors. Available in: <https://doi.org/10.1016/j.trip.2019.100036>.

TOLLS, Tolls calculation in Portugal, Spain and France, respectively, in https://www.estradas.pt/; https://www.autopistas.com/;https://www.autoroutes.fr. .

TRANT, G., RIORDAN, K., (2009). Feasibility of New RoRo/RoPax Services between Ireland and Continental Europe. .

UNITED NATIONS, (2001). Transports Combines, Terminology on Combined Transport, Kombinierten Verkehrs. **New York**, p. 18.

UNITED NATIONS, (2004). Glossary for transport statistics (3rd edition). , p. 116 pages.

WIŚNICKI, B., CHYBOWSKI, L., MILEWSKI, D., HEŁCZYŃSKI, I., (2017). Koncept razvoja mreže intermodalnog transporta oslikan tržištem Poljske. **Nase More**, v. 64, n. 1, p. 33–37.

WIŚNICKI, B., MILEWSKI, D., (2018). Assessing the Economical Efficiency of Intermodal Chains in Global Trade. **SHS Web of Conferences**, v. 58, p. 01032.

YPSILANTIS, P., ZUIDWIJK, R., (2019). Collaborative fleet deployment and routing for sustainable transport. **Sustainability (Switzerland)**, v. 11, n. 20.

ZHANG, M., PEL, A. J., (2016). Synchromodal hinterland freight transport: Model study for the port of Rotterdam. **Journal of Transport Geography**, v. 52, p. 1–10.

ZHANG, R., JIAN, W., TAVASSZY, L., (2018). Estimation of network level benefits of reliability improvements in intermodal freight transport. **Research in Transportation Economics**, v. 70, n. September, p. 1–8.

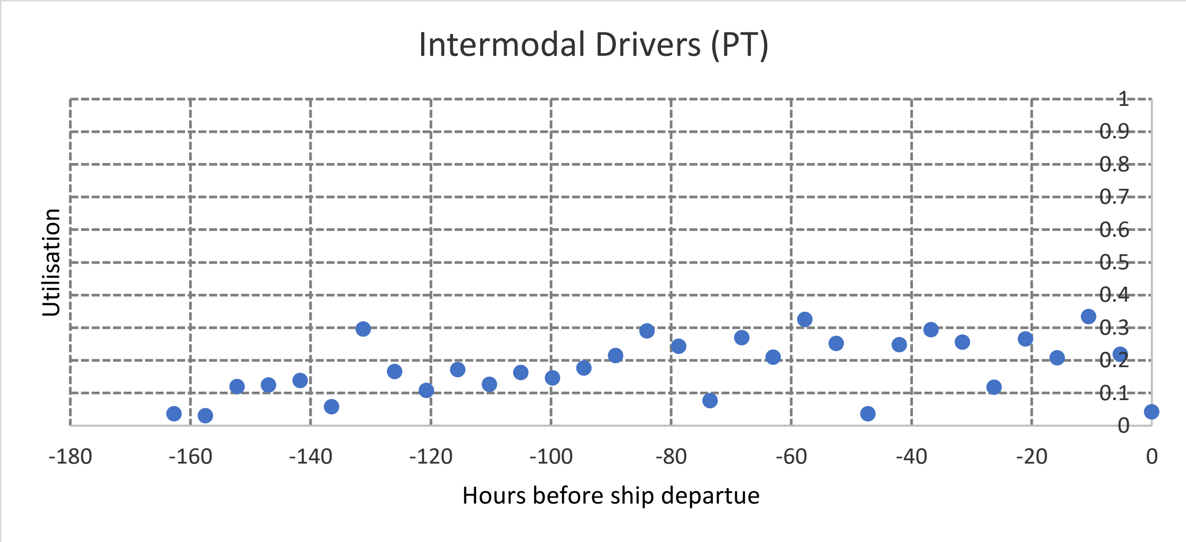
APPENDICES

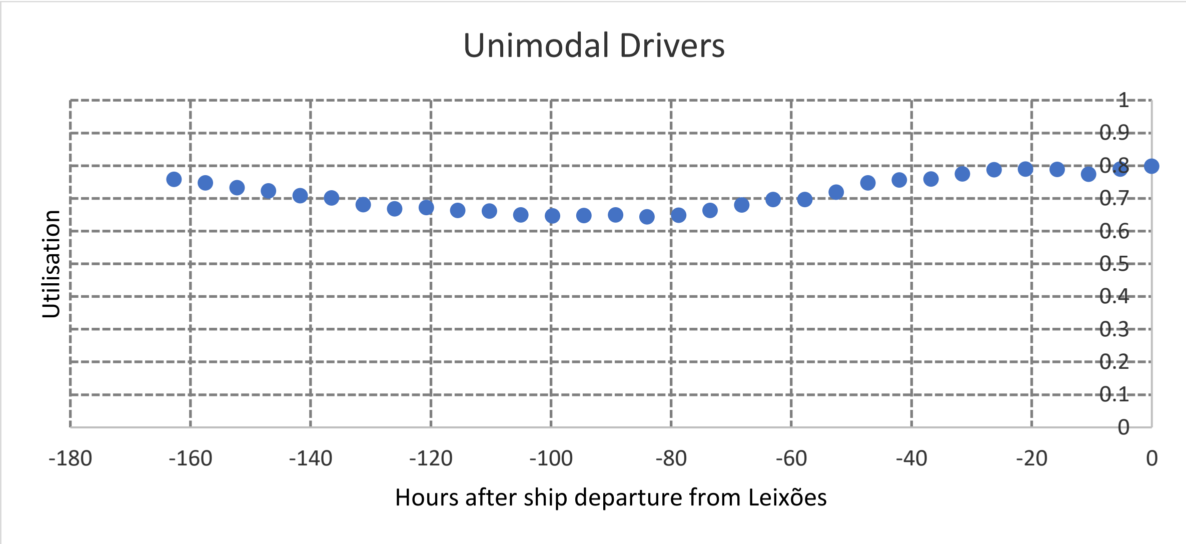
APPENDIX 1 – DETAILS OF MARITIME ROUTES

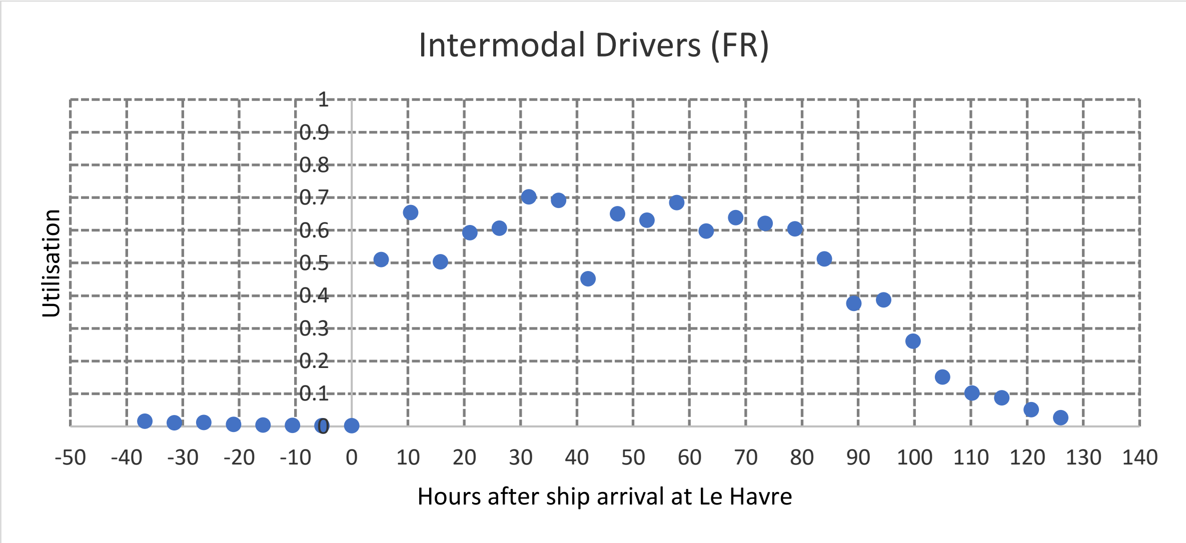
Distribution of cargo units to be carried between pairs origin-destination:

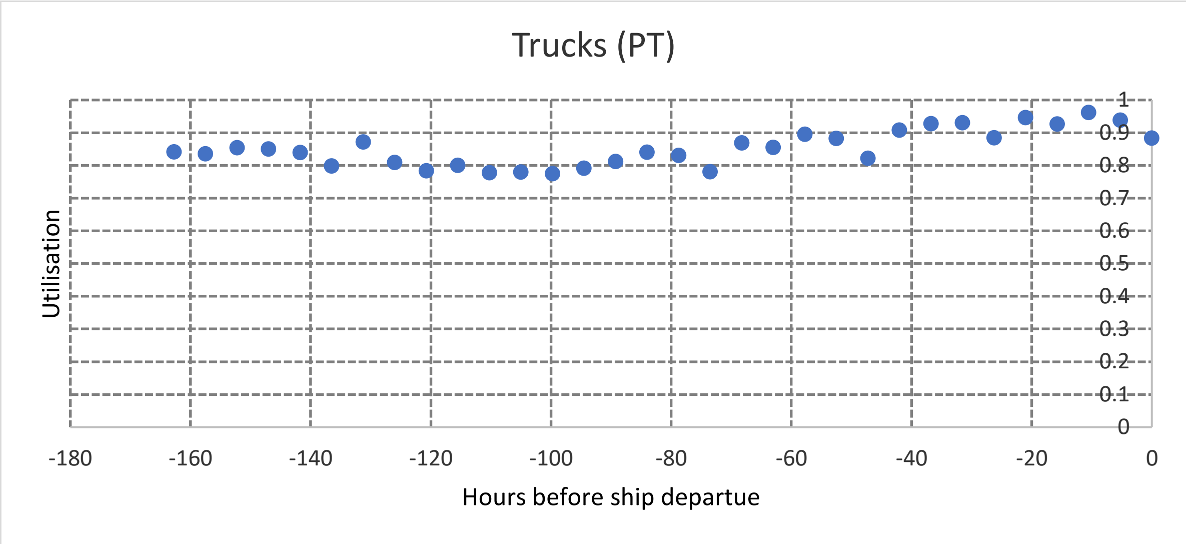
	Brussels	Luxembourg	Troyes	Paris	Le Mans	Amiens
Viana do Castelo	24	48	24	72	48	24
Guimarães	96	144	24	192	48	96
Amarante	48	24	72	120	72	24
Oliveira de Azeméis	24	48	24	24	48	72
Aveiro	120	72	144	192	24	48
Leiria	24	72	72	120	48	24
				Total/year		**2400**

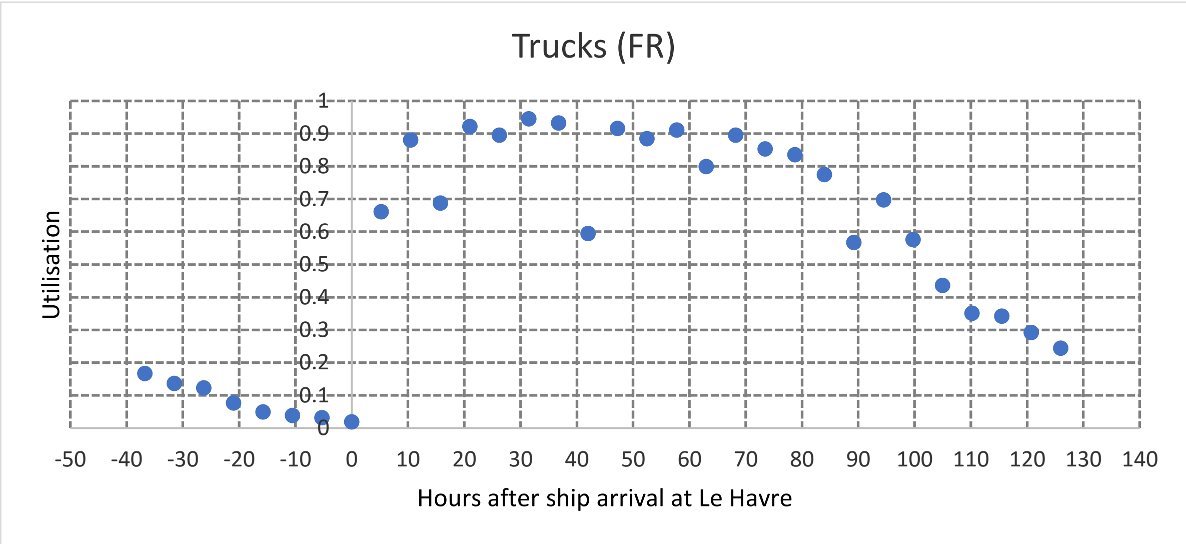
APPENDIX 2 – UTILISATION PLOTS OF THE INTERMODAL CONFIGURATION NUMBER 18.








Trucks (PT)
Utilisation
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-180
-160
-140
-120
-100
-80
-60
-40
-20
0
Hours before ship departue


Trucks (FR)
Utilisation
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-50
-40
-30
-20
-10
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
Hours after ship arrival at Le Havre