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Exploring the Added-value of Synchromodality with Micro-Simulation

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Abstract

Synchromodality introduces the notion of real-time adaptive mode choice into the production of freight transport services. It is gaining in popularity, but understanding of the potential advantages of this concept remains limited.

We propose a new hybrid micro-simulation model of a freight transport market that combines agent-based technology with a discrete event approach. The market is populated with organisers of freight transport services, which hire on-demand transport agents.

The model was calibrated to recreate the market conditions of the Atlantic Corridor of the TEN-T. A set of experiments was run under different market conditions, for three types of organisers: one intermodal and two synchromodal. The services were evaluated against two performance variables: price and transit time.

The results reveal the added-value of the synchromodal concept in both performance variables and suggest that its potential benefits depend on the features of the network, the customer requirements, and the characteristics of the concept.

Keywords: Synchromodal Transport; Agent-based Modelling; Discrete Event Simulation; Freight Transport.

1. Introduction

Synchromodality is a recently formulated concept of freight transport chains (Tavasszy *et al.*, 2010) that adds the notion of adaptive mode choice to previously existing concepts, such as intermodal freight transport. Essentially, mode choice is made simultaneously with the production of the transport service, based on real-time information on the current conditions of the transport system (e.g., delays, congestion, transit times, pricing, availability, etc.), blending together organisation and coordination. Organisation is brought more into sync with the moment of production, enabling decisions to be based on up-to-date information. Coordination is proactive, and monitors the planned transport chain against the real conditions. Problems or opportunities can be identified early, and corrective measures may be implemented in the following leg. The configuration of the transport chain is, therefore, not fixed, but is continuously adapted to the real conditions of the transport system. The outcome is a more efficient service that takes into account demand requirements and supply conditions (Reis, 2015).

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However, severalchallenges may hamper efficiency, raise production costs or reduce market opportunities for synchromodal transport. Some of these are common to other concepts of multimodal freight transport chains, such as shipments consolidation and the cost of transhipment operations(Woxenius, 1998; Asariotis, 1999; Slack, 2001; Capineri and Thomas, 2006; Reis *et al.*, 2013); while others are specific to synchromodality, including insufficient technological interoperability, or restrictions arising from thecontractual structurecurrently in place[1](Tavasszy, Behdani and Konings, 2015; Pfoser, Treiblmaier and Schauer, 2016). Nevertheless, there is a growing interest inthe concept, which is largely fuelled by the expectable gains.

The numberof publications on boththe ISI Web of Science[2] (a total of 28) or on Scopus[3] (a total of 42) reference databases is somewhat limited, mirroring the yet limited knowledge onthe concept. Further research is necessary to enable a better understanding of synchromodal transport, in particular, with regard tothe expectable gains and how they could be achieved.The review of the literature revealed a limited number of analytical studies (e.g., Zhang and Pel, 2016),with existing transport models focusing on routing and service schedule optimization, and not conveniently capturingthe specific dynamics of synchromodal transport, in terms of real-time organisation and coordination.

This manuscript aims tocontribute to the mitigation ofthis gap, andpresents the results of research aimed at assessing the potential performance advantage of synchromodalityvis-à-vis intermodality. A new micro-simulation model was developed to measure the performance of each concept, and data from the Atlantic Corridor of the Infrastructure Trans-European Network - Transport (TEN-T) was used in the scenario development.

The model makes use of Discrete Event Simulation (DES) and Agent Based Modelling (ABM) techniques, simulating a freight transport market with time-varying demand and supply. Specific efforts were made to simulate the role of the freight transport service organisers – i.e., freight forwarding – responsible for the real-time organisation and coordination. In DES, a system's variables change atspecific points in time (Sakurada and Miyake, 2009). From a conceptual point of view, the organisation and production of a freight transport chain can be represented as a process (i.e., a set of parallel and/or sequential activities that occur ata specific time) (Manheim, 1979; Jensen, 1990; Woxenius, 1998). Freight transport markets havealso already been successfully studied usingABM (Gambardella, Rizzoli and Funk, 2002; Davidsson *et al.*, 2008; Baindur and Viegas, 2011; Cavalcante and Roorda, 2013; Holmgren *et al.*, 2013; Reis, 2014). In this research project, ABM was used to simulate: i) the logistic operator agent'sbehavioural properties (e.g., price formation, negotiation, decision making process, etc.); and ii) the geographical components of the market (i.e., terminals and ports). The outcome is a hybrid micro-simulation model that uses selected capabilities of the ABM technology to strengthen the DES modelling approach.

The paper is organised as follows. Section 2 briefly reviews the literature on synchromodal transport. Section 3 describes the key characteristics of the synchromodal corridor – in this case, the AtlanticCorridor – to be used for the model. Section 4 explains the key assumptions and design principles, including the agents' behavioural algorithms; also in this section, the model'svalidation efforts are described. The results of the experiments are discussed in Section 5. Finally, Section 6 summarises the main conclusions of the research and recommends directions for further research in this area.

[1] Section 2 discusses the main challenges and barriers to the production of synchromodal transport.

[2]Search by: "synchromodal" and "synchromodality" in manuscript titles, abstracts and keywords. Search at Web of Science Core Collection. All years. Search done in July 2018.

[3] Search by: "synchromodal" and "synchromodality" in manuscript titles, abstracts and keywords. Search at Scopus Database. All years. Search done in July 2018.

2. Literature Review on Synchromodal Transport Concept

Real-time decision making in freight transport, logistics and supply chain management is not a novelty. Indeed, several concepts, such as seamless or lean supply chains, or integrated information material flow, already require real-time information onthe freight flows.This is described by Singh and van Sinderen (2015) as “context awareness”, meaning the transport plan may need to be adapted to better suit the conditions currently observed in the system. The innovation in the concept of synchromodal transport resides inthe fact that, for the first time, it offers theflexibility to freely switchtransport modes during the production of the freight transport service, based on real-time information.

The concept of synchromodal transport is still inits infancy, in a stage of development that the philosopher Kuhn would describeas pre-paradigmatic (Kuhn, 1962). Distinguishing characteristics of this stage include lack of consensus ondefinitions, hypothesis, or methods, as evidenced in Table 1.

Table 1: Synchromodal transport concepts

Definition	*Source*
“In synchromodal transport, the logistics service company is able to deploy various transport modalities real-time and to exchange them if reasons arises to do so (i.e., up-to-date traffic information)”	DINALOG (2015)
“synchromodal emphasises the real-time aspect of the transport”	Harris *et al*. (2015)
“intermodal planning with the possibility of real-time switching between the modes or online intermodal planning”	Riessen *et al*. (2015b, 2015a)
“is positioned as the next step after intermodal and co-modal transportation, and involves a structured, efficient and synchronized combination of two or more transportation modes. Through synchromodal transportation, the carriers or customers select independently at any time the best mode based on the operational circumstances and/or customer requirements”	Steadie Seifi *et al*. (2014)
“can be achieved by making modality choices according to the latest logistics information, e.g., transport demands, traffic information, etc.”	Li *et al*. (2013)
“moves one step forward from intermodal freight transport by adopting the mode-free booking concept and allowing timely switching among available modalities according to the real-time information of the freight transport process”	Li *et al.* (2017)
“an innovative, promising idea of flexible and sustainable utilization of transport resources based on the co-operation of carriers representing various transport modes, adjusted to customer requirements and current transport capacities”	Pleszko (2012)
“the supply of services of the various modalities is synchronized to a cohesive transport product, which meets at any moment the transport demand of shippers in terms of price, punctuality, reliability and/or sustainability. This synchronization includes both the planning of services, the performance of services and the information about services”	Burgh (2012)
“an integrated view in planning and using different transport modes to provide the flexibility in handling transport demand. Therefore, synchromodality improves the performance and robustness of logistics by taking advantage of the complementary nature of multiple transport modes”	Behdani *et al*. (2016)
“It refers to creating the effective, efficient and sustainable transportation plan for all orders by using real-time information. (…) the mode combinations for orders can be changed before or during the transportation in case of disturbances”	Guo *et al*. (2017)

The negative consequences of multiple co-existent definitions arediscussed in Reis (2015) and Singh *et al.*(2016). The evolution towardsKuhn’s normal stage requires the accrual of further knowledge on the topic, so that a consensus could be reached.Additionally, some of the references found – e.g. Harris *et al.*(2015) and Steadi Seifi *et al.*(2014) – merely explore synchromodality as a concept, or simply discuss the characteristics its practical implementation should observe – e.g. Burgh (2012) and Pleszko (2012).

The implementation of synchromodal transport impliesthat a set of requirementsis met, relating toinfrastructure, contracts, organisation and technology. A brief reflection on each requirement is presented below.

- **Infrastructure requirements**

As far as the infrastructure requirements are concerned, a synchromodal transport network is composed of corridors and terminals. The corridors offer services of varying quality, in terms of frequency, capacity or reliability. The terminals connect the various modes that serve the corridor. Terminals should be equipped with the appropriate equipment so that, in the event of disturbances (due to infrastructure congestion, delays, or cancellation of services, for instance), it should be possible to quickly transfer the cargo to the most appropriate mode of transport. Ultimately, the choice of corridors depends on the existing infrastructure (such as terminals and warehouses) and the transport equipment provided by the carriers (in terms of fleet's size and characteristics), as well as their suitability to withstand the flows foreseen for each connection (Burgh, 2012).

- **Contracts requirements**

In synchromodal transport, modalities are engaged in a flexible and coordinated way; this is only made possible with the use of mode-free booking, whereby the shipper books transportation capacity within the network, but does not choose a specific mode to make the transport service.However, in structural terms, current freight transport contracts are formulated within a paradigm in which the modalities remain constant throughout the transport service. Furthermore, international transport conventions, which give legal support to transport service contracts, are also mode specific (Güner-Özbek, 2011). Modifications to contracts, whilstpossible, are costly and not a convenient possibility given the timings involved in synchromodal transport; therefore,new forms of contracts allowingfor the change of modeswithout penalty are needed. Another issue is the pricing of synchromodal transport:by permitting diversions from the initial transportation plan, the associated costs are unlikely to be in line with anticipated costs. Thus, it will be necessary to adjust the contracts between agents to reflectthis new reality.

- **Organisation requirements**

Synchromodal transport adds the complexity of the real-time decision, as the freight transport organiser must be able to make decisions in a short period of time. The integration is not limited to one transport chain (as in intermodal transport), but encompasses all the available services(Guo, Van Blokland and Lodewijks, 2017), and sometimes multiple chains, in order to offer mode choice flexibility. Another organisational challenge relates to the divergence in terms of thetechnical parameters of the vehicles to be used during transport (such as dimensions, weight and cooling capacity). In addition, potential infrastructure restrictions make it difficult to coordinate the consolidation processes to be carried out at each stage of the journey, and may result in increased costs (Pleszko, 2012).

- **Technology requirements**

The success of synchromodality depends on the reliable exchange of information in real-time about the transport service and network (e.g., infrastructure congestion, delays and cancellation of orders). Such a requirement calls forinteroperability between the transport agents' information and communication systems(Singh & van Sinderen, 2015). However, interoperability difficulties remain a key problem at the European Union level, due to a lack of standard communication protocols or common rules for building static or dynamic datasets (Digital Transport & Logistics Forum, 2015; European Commission, 2016).

Existing literature on synchromodal system simulation islimited; the few available transport models for synchromodal services focus on service scheduling and order assignment optimisation. Literature on intermodal networkswas also included in the literature review, and taken into accountinthe model's conception.

Li *et al.*(2013) propose a general framework model the dynamics of the intermodal transport network, in order to achieve the optimal routing of containers. A similar methodology was later adopted by Nabais *et al.*(2013), whose work considered the importance of the prediction horizon in the planning process, and the role of hubs in the network (*i.e.*for the consolidation and forwarding of cargo). The developed framework simultaneously guarantees on-time cargo delivery and sustainability requirements imposed by current government policies. The proposed Model Predictive Control (MPC) model takes an optimisation-based approach to the cargo assignment problem, considering three components: assignment priorities are influenced by the shipments' due date and destination; the transport modalities, whose environmental impact may be penalised; and the connection schedules, which may have different costs. In a subsequent study, Nabais *et al.*(2013)developed the previous framework, now stipulatinga desired modal split, in order to comply with environmental policies. A new variable was added to control cargo in danger of not meeting the deadline, the so-called lost cargo. In this variation, there is a need to take into account past decisions regarding cargo assigned to each modality, so as to re-assign lost cargo while respecting the set modal split. The application of bothformulations to a simulated networkconfirmedthe importance of information gathering and demand forecast: the increase of the prediction horizon allows the forwarding of cargo at the hubs, whichreduces the occurrence of lost cargo, as well as cargo peaks at terminals; this reduction inurgent cargo leads to a higher flexibility of the network, and to more sustainable modalities being preferred.

Riessen *et al.*(2015b) focused on the service network design, proposing amodel to assess the effects of additional intermediate transfers between terminals. This model combines elements of Minimum Cost Network Flow (MCNF) and Path Based Network Design (PBND) models, which enable, respectively, the flexible routing of cargo over several links of the networks, and the predetermination of a set of feasible paths that reduces decision variables. Two new features are introduced: the possibility of late delivery (with a penalty); and the use of subcontracted services (to increase flexibility). The resulting optimization model attempts to minimize overall transportation costs. Its application showed that the use of intermediate transfers reduces transit costs,andthat, in turn, the reduction intransfer costs significantly increases the number of performed intermediate transfers.In a subsequent research project, Riessen *et al.*(2015a) adapted the previous model to include the real-time switching aspect that characterises the synchromodal solution, creating a new formulation: Linear Container Allocation model with Time restrictions (LCAT). This LCAT model assesses the effect of disturbances onthe operational planning, by evaluating two dimensions: impact, the additional costs resultingfrom the occurrence; and relevance, which compares the costs of reassigning all cargo *versus* making a local re-planning of only the affected shipments. The model was appliedto assess the effects of two types of disturbances: service cancellation, and out-of-schedule departure. It was concluded that these types of disturbances usually have a low relevance, and, accordingly, the full update of assignments did not perform significantlybetter than the local updates. Both Behdani *et al.*(2016) and Fan (2013) published very similar reports, which can be considered complementary to Riessen *et al.*'s (2015b) formulation. In their publications, they developed an optimization model to schedule 3 modalities (barge, rail, and truck) that serve the same OD. Considering the different characteristics of each route (in terms of transit time, cost, capacity, etc.), the challenge of the model is to find the schedule and timing of services that minimizes transportation costs, while ensuring a minimum level of service quality (by penalizing delays and unnecessary waiting times at the terminals). The developed modelwas tested against two scenarios: with no coordination between modes, and with sequential scheduling. It was concludedthat an integrated service scheduling was able to reduce the use of trucks, as well as the waiting penalties, leading to lowertotal transportation costs.

Spikker (2014) developed a DES modelto simulate the transport of freight across the Blue Banana Corridor, whichruns from the UK to Italy, and is served by 3 modes (barge, rail, and truck). The developed model aims to reproduce the transport of several orders along the corridor in the most cost-effective way. The performance of the planning solution was evaluated according to a set of keyindicators: the numberof arrivals to the destination before the deadline measure the reliability (or service level); the transport cost, including handling and transhipment costs; the carbon emissions, to assess the environmental sustainability of the solution; and the fraction of synchromodal transport, to evaluate the degree of employment of the barge and rail modes. The developed model was tested for 3 types of planning: direct routing; non-consolidated synchromodal planning; and consolidated synchromodal planning. It was concluded that synchromodal solutions generallyperform better forall indicators, except reliability, achieving greater cost and emissions reductions. It was also found that synchromodality shows better results than direct routing for longer routes, and especially for larger orders, benefitting greatly from the reduction intranshipment costs.

In a more recent approach to the assignment optimisation problem, Li *et al.*(2017) expanded their previous framework to incorporate the cooperation between transport agents. In this model, each agent aims to maximize their individual goals (or minimize their operation costs) while taking into account that some sub-optimal solutions may provide a better contribute to achieve the global objectives of the network. This is attained by linking (interconnecting) the variables and constraints in the optimization functions of different agents. Perez Rivera and Mes(2017) focused on the issue of the impact of demand forecasting in the logistic operators decisions. The developed optimization model took and "anticipatory" approach to the planning problem, by incorporating predictions on future demand into the current date's decisions; thus, the logistic operator may opt to forward or postpone shipments, in order to minimize operation costs according to the expected evolution of demand. Both studies focussed on the selection of the most adequate algorithms to perform the optimization run.

The review of the literature revealed a preference towardsoptimisation models. Typical purposes include cost minimisation or optimal fleet and scheduling planning. Conversely, few models aimed at evaluating the dynamics of synchromodality, such as real-time decision making, and its effects in the (long-term) performance of the supply chain.

3. Synchromodal transport corridor

As described in Section 1, the investigation focused on the TEN-T Corridor #4 - Atlantic Corridor. This corridor traverses three European Union member states, establishing the rail freight connection between the main ports on the Portuguese coast, as well as the remaining Portuguese, Spanish and French ports and terminals, linking the Iberian Peninsula to the French-German border. Currently, there are no regular services linking Portugal with France or Germany;hence, the interest inunderstanding whether synchromodal transport could attract transport and logistics companies onto the corridor.

In the absence of a rail transport market, we formulated a synthetic freight transport market with regular (and increased frequency) rail and maritime transport services. The simulation model development was aided with the information garnered in the study conducted by BG (2016), which contains real data on the characteristics of the road and railway infrastructure in the Iberian Peninsula and in France, as well as the operations carried out in the network. Where real information was unavailable, namely the sea transport mode characteristics, expert judgement was sought to assist in the construction of plausible values.

The developed uses a simplified representation of the Atlantic Corridor, considering a singlebranch linking Lisbon to Forbach. Figure 1 presents the simulated transport network and terminals, which is served bythree modes – rail, road and sea transport.

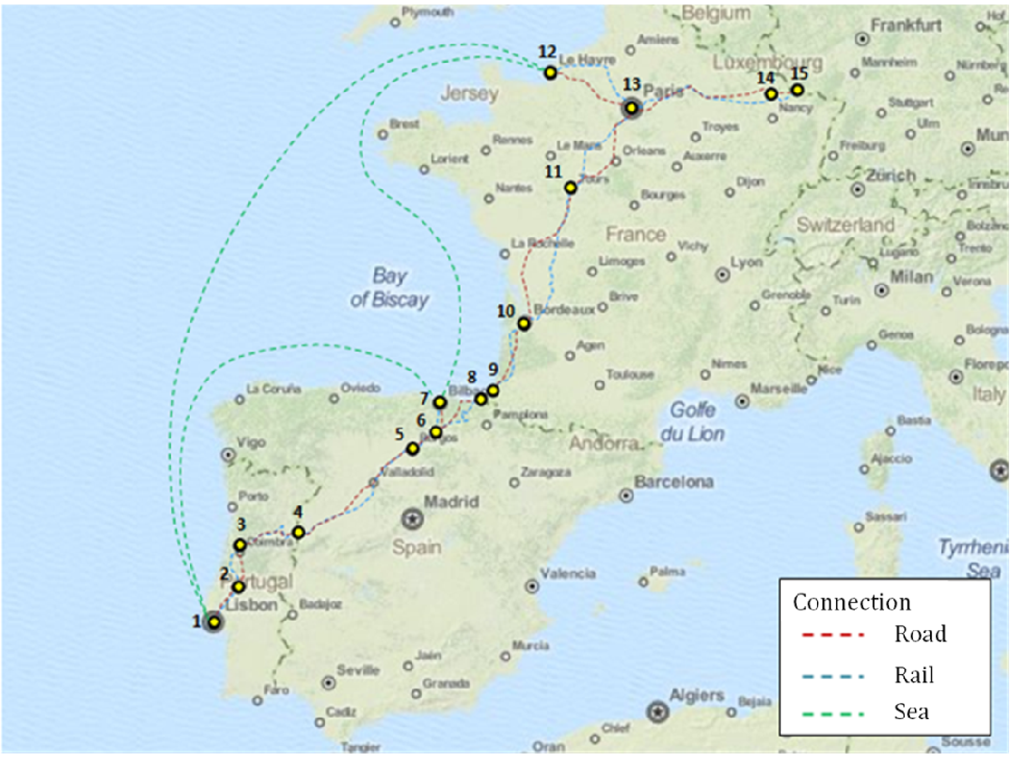

Figure 1:Synchromodal transport corridor

We considered a total of fifteen terminals along the rail corridor (Table 2). Every terminal isserved by road and rail services;additionally, three of them arealso ports, and are thusserved by maritimetransport. Terminals on both sides of a border were considered as asingle terminal.

Table 2: Terminals in the Case Study

ID	*Name*	*ID*	*Name*	*ID*	*Name*
1	Lisbon (Port)	*6*	Bilbao (Port)	*11*	Tours
2	Entroncamento	*7*	Miranda Ebro	*12*	Le Havre (Port)
3	Pampilhosa	*8*	Irún – Hendaye	*13*	Paris
4	Vilar Formoso – Fuentes de Oñoro	*9*	Bayonne	*14*	Metz
5	Burgos	*10*	Bordeaux	*15*	Forbach

Only the transport in the direction from Lisbon to Forbach was considered. With this configuration, fifteen road connections, twelve rail links and three sea connections were established, as shown in **Errore. L'origine riferimento non è stata trovata.**. The schedule published by the Management Board forthe Corridor indicates that the rail services do not stop at every terminal, hence the disparity in the number of road and rail links. Finally, in terms of freight transport distribution, we assumed that goods originated in Portugal (terminals 1 to 4), with destination inFrance (terminals 9 to 15). No services between Portugal and Spain or internalservices were considered.

Table 3: Links between terminals (by mode)

Mode	*O- D*	*Link*	*O-D*	*Link*
Road	1 - 2	Lisbon – Entroncamento	8 - 9	Hendaye – Bayonne
	2 - 3	Entroncamento – Pampilhosa	9 - 10	Bayonne – Bordeaux
	3 - 4	Pampilhosa – Vilar Formoso	10 - 11	Bordeaux – Tours
	4 - 5	Fuentes de Oñoro – Burgos	11 - 13	Tours – Paris
	5 - 7	Burgos – Miranda Ebro	12 - 13	Le Havre – Paris
	6 - 7	Bilbao – Miranda Ebro	13 - 14	Paris – Metz
	7 - 6	Miranda Ebro – Bilbao	14 - 15	Metz – Forbach
	7 - 8	Miranda Ebro – Irún		
Rail	1 - 2	Lisbon – Entroncamento	7 - 6	Miranda Ebro – Bilbao
	2 - 3	Entroncamento – Pampilhosa	7 - 8	Miranda Ebro – Irún
	3 - 4	Pampilhosa – Vilar Formoso	8 - 13	Hendaye – Paris
	4 - 8	Fuentes de Oñoro – Irún	8 - 15	Hendaye –Forbach
	5 - 8	Burgos – Irún	9 - 15	Bayonne – Forbach
	6 - 7	Bilbao – Miranda Ebro	12 - 14	Le Havre – Metz
Sea	1 - 6	Lisbon – Bilbao	6 - 12	Bilbao – Le Havre
	1 - 12	Lisbon – Le Havre		

4. Simulation Model Presentation and Specification

The model proposed in this study aims to reproduce a real-world supply chain, encompassing the operations performed by each agent in the network, as well as their interactions. Specificefforts were made to simulate the logistic operator's decision-making process, and to integrate it into the production of the transport service. The following sections describe the structure and parameterization of the developed model.

4.1 Model Assumptions

Bearing in mind that the model aims to recreate the dynamics of a freight transport chain, the following assumptions were adopted:

- The model is populated with six categories of agents. These agents may be cognitive: Intermodal Transport Operator (ITO) and Synchromodal Transport Operator (STO); or non-cognitive: Customer, Carrier and Terminal.
- The non-cognitive agents behave according to a pre-defined logic, performing a sequence of tasks little affected by external events, whereas a cognitive agent has the ability to make its own decisions(Wahle *et al.*, 2002), its behaviour deriving from its perceptions of the environment and the information conveyed by the remaining agents.
- The population of each agent categoryis variable: a single Transport Operator Agent (ITO and STO) operates the network; three Carrier Agents are considered, each representing a transportation mode, while each transhipment terminal is operated by a separate Terminal Agent; as Customer Agents are linked to orders being transported in the network, this agent population varies between (and during) simulation runs.
- The Customer Agent generates the daily demand of freight transport services. Its behaviour follows a process flow – based on discrete event principles.
- The Transport Operator Agent (ITO and STO) organises and manages the transport services, determining the way orders will be handled by the remaining elements of the network. They assign orders to services based on a set of factors, such as pricing or expected time of delivery.
- The Carrier Agent represents a transport company that conveys goods between designated geographical locations (which correspond to the Terminal Agents' locations). Each Carrier Agent operates one mode of transport.

- The Carrier Agents either work with fixed timetables or not, and are respectively designated as regular or flexible services.The vehicle of a regular Carrier Agent may convey several orders; whereas the vehicle of a flexible Carrier Agent solely conveys single orders.

4.2 Model Architecture

The model was structured in two interrelated and connected layers: the administrative layer and the physical layer (Figure 2). This conceptualisation of a freight transport service was initially proposed by Manheim (1979) and since adopted by other authors (Jensen, 1990; Woxenius, 1998; Bergkvist *et al.*, 2004; Baindur and Viegas, 2011; Reis, 2014). The administrative level encompasses those tasks that are not directly related withthe physical transport of goods, such as inquiries, ordering andbooking. The physical level includes the activities carried out during the physical transport of the freight, such as transport and handling. Figure 2 presents both the positioning of each agent in the layers, and the key interactions among them.

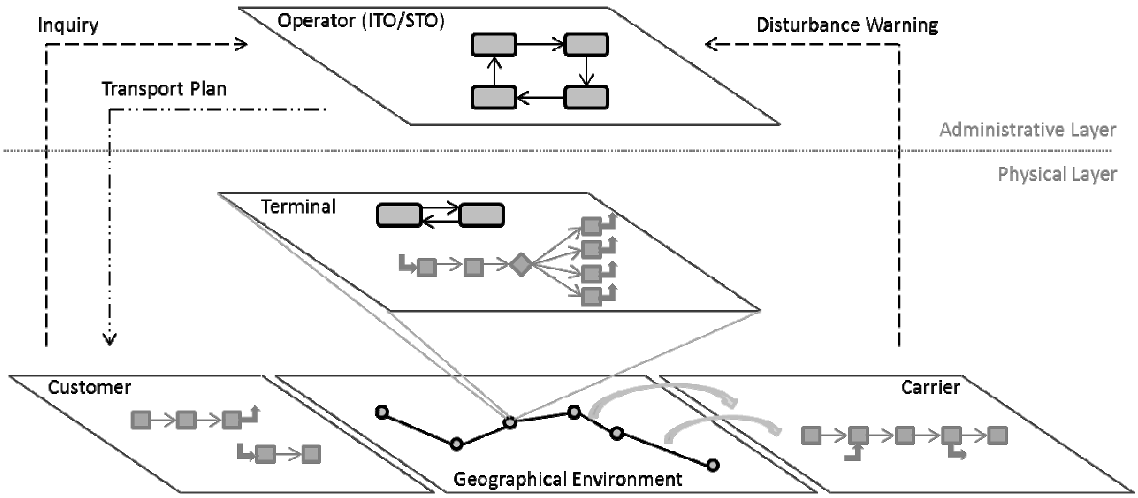

Figure 2: Conceptual structure of the simulation model

As discussed in Section 1, the model was developed using DES and ABM techniques. Each modelling technique was deployed for different agents as follows:DES to model the behaviour of Customer, Carrier and Terminal Agents, and ABM to model the behaviour of Operator and Terminal Agents.

The model was developed with Any logic Software 7[4].The description of the model hereinafter follows the natural division of agent-based models: agents, environment, and interactions. A fourth part was added to describe the decision-making simulator, implemented for the Operator Agents.

4.3 Agents

The developed model is populated by fourdifferent types of agent: Customer, Operator(ITO or STO), Terminal and Carrier. Each agent’s behaviour is defined by the process flow established in the correspondent module; these modules interact with one another, as illustrated in Figure 3.

[4] Further information available at www.anylogic.com (accessed on July 2017).

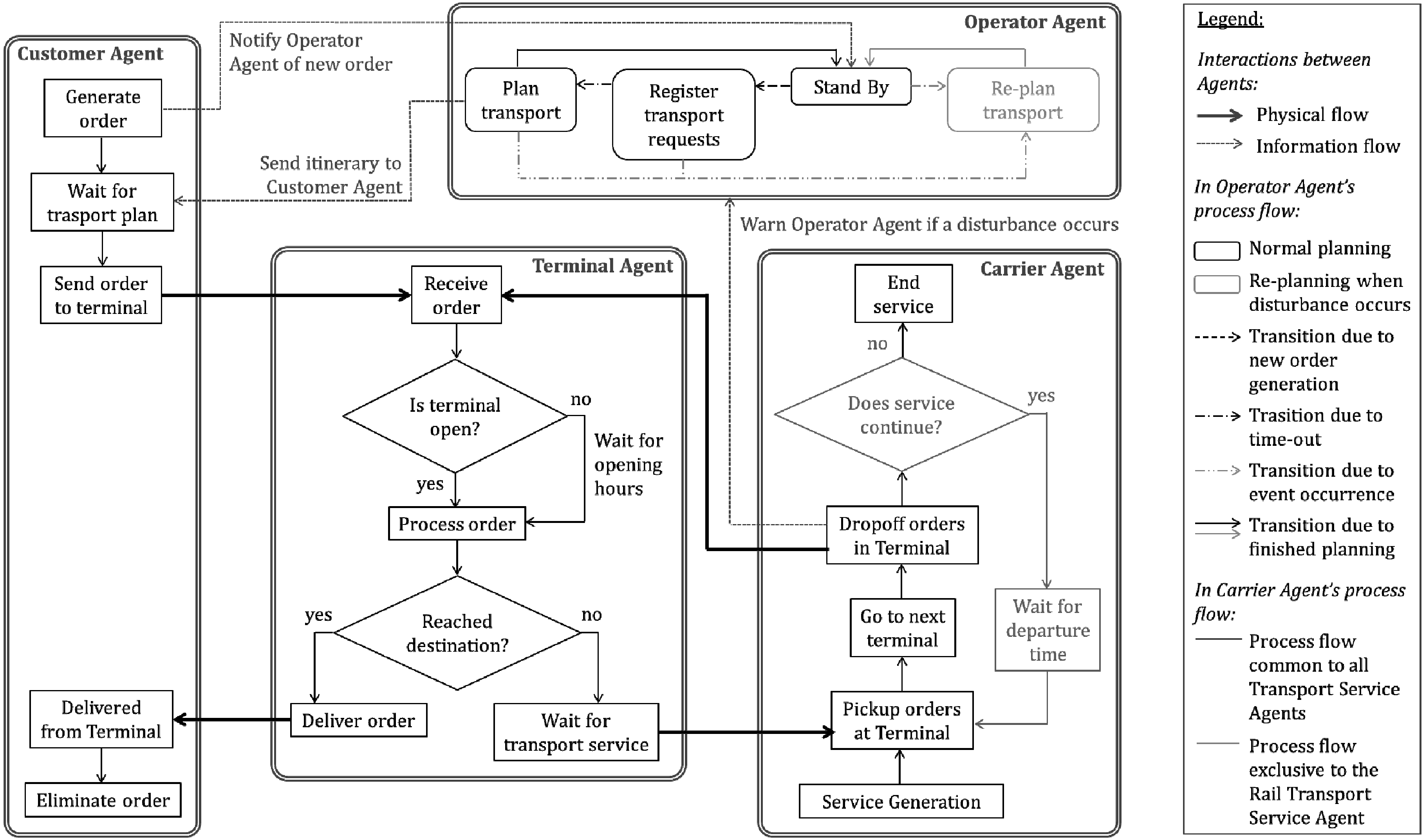

Figure 3: Agents' process flows

4.3.1 *Customer Agent*

This non-cognitive agent generates the shipment orders, and was modelled using DES. Whenever a new order is generated, the Customer Agent sends a message to the Operator Agent, conveying the order's specifications (Figure 3). The Customer Agent then waitsfor the arrival of the transport plan (from the Operator Agent) and sends the cargo to the origin terminal once the pickup date is reached. After the containers arrive at thedestination, the corresponding Terminal Agent notifies the Customer Agent, who formalises the order's reception.

Each shipment order is characterised by a set of attributes:

Weight is randomly generated through a uniform distribution function.

Origin is randomly selected from the possible origins (i.e., terminal 1 to 4).

Destination is randomly selected from the possible destinations (i.e., terminal 9 to 15).

Pickup and Delivery timings are determined at the moment of generation of the order, usinguniform distribution functions;their interval is set at the beginning of each simulation run.An order may be generated onthe same day of transport (pick up date equal to zero). The objective was to test the transport chain'scapacity of response.It was assumed that goods should be delivered by18:00 onthe delivery date.

4.3.2 *Transport Operator Agents - ITO and STO*

These Agentsare the organisers (e.g., freight forwarders) of the transport services, responsible for planning and monitoring the transport services.Aslogistic service providers, they are required to be in tune with the events occurring throughout the network, and to act accordingly; thus, their decision-making processes were modelled through ABM. Both agent types (ITO and STO) have the same decision-making process, they differ, however,as to how the tasks are executed.

Shipment orders coming from the Customer Agent are continuously loaded into the Register Transport Request state (see Figure 3). The Operator processes the received orders every 12 hours: this allows for the registered orders to be processed in batches, permitting for a more efficient utilisation of the available transport capacity (in Section 4.6.1, we describe the sorting rules). In the Plan Transport state, the Operator Agent selects the most advantageous transport servicesfor each order.

During the execution of the service, the Operator Agent monitors the service. When a disturbance occurs (e.g., delay or service cancellation), it switches to the Re-plan Transport state, whereall affected orders are re-planned,aiming at guaranteeing compliance with the delivery date.The re-planning task differs for ITO and STO Agents, since they have, by definition, access to different information and different managerial capabilities. The decision-making logics for both the priority assignment and the selection of itineraries during the planning and re-planning processes are further elaborated upon in Section 4.6.

4.3.3 *Terminal Agent*

The Terminal Agent is responsible for handling the goods (Figure 3). This agent was modelled using DES (to reproduce loading and unloading activities) and ABM (to represent its working period): it may receive cargo at any time, but only performs transhipment operations and administrative tasks during working hours (Table 4). For each arriving order, the Terminal Agent checks the destination:if the destination is the current location, it is then delivered to the corresponding Customer Agent;otherwise (meaning that the terminal in question is just a transhipment point), the Terminal Agent checks the order's itinerary to assess which mode will perform the next stage of transport. The order is then queued to be collected by the next transport service.

The Terminal is characterised in the model by the following attributes:

ID identifies the Terminal in the system.

Location corresponds to the Terminal's location in the network.

Opening and Closing Hours define the working hours of each Terminal; for the research presented herein, the working hours were defined as follows (Table 4).

Table 4: Terminal operating schedules

Terminal	*Opening*	*Closing*	*Working period*
Bayonne, Bordeaux, Tours	10:00	02:00	16 hours
Remaining Terminals	00:00	23:59	24 hours

4.3.4 *Carrier Agent*

The Carrier Agent is in charge of moving goods between locations, and was modelled through DES.The process flow presented in Figure 3 is typical for this type of agents. Delays (and consequent notifications of the Operator Agent) are simulated as follows:at the end of each service, the actual arrivaltime to the Terminal (current time) is calculated;if the actual arrival time is later than the estimated arrival time (such that the order can no longer be picked-up by the next service in the itinerary), or the deviation (positive or negative) between the actual and the estimated arrival times exceeds 10 minutes, then a message will be sent to the Operator Terminal.

Threedifferent modes were taken into consideration in the model:

Truck Vehicle is a flexible service, only generated when an order enters the waiting queue inthe Terminal Agent's process-flow.It performs a single movement from its location to the next terminal on the network, terminatingthe service upon arrival at that terminal.

Ship Vehicle isa regular service, being generated in accordance to the predefined schedule.The vehicle is createdregardless of the amount of available orders waitingfor transport. As with the Truck Vehicle, the Ship Vehicle performs a single point-to-point journey.

Train Vehicle also presents a regular service. Unlike the previous vehicles, a train's schedule includes multiple stopovers, but not necessarily all intermediate terminals. As such, the process flow of this Vehicle presents an additional loop (see Figure 3), where, upon arrival at the terminal, it verifies if this is the final destination of the service.If so, then the service is terminated; otherwise,there are transhipment operations and the Train Vehicle proceeds to the next terminal onthe journey.

Each transport element is characterized by the following attributes:

Capacitydefines the maximum weight that can be loaded oneach vehicle.

Speed of movement of Trucks and Ships between terminals is defined according to stochastic distributions.

Service Scheduleof sea and rail services:it defines the terminals where the vehicles are to stop, as well as the expected arrival and departure times at each stop. Services are expected to depart on time, but deviations from the schedule are possible during the course of the transportation; excessive delays in intermediary terminals may cause the cancellation of Rail services.

Price of the transport service, includes a penalization related to carbon emissions.

Transhipment Priceat terminal is considered constant:the price for a tonne is €3.90.

In

Table 5 are presented the values used in the developed model.

Table 5:CarrierAgents' attributes

Mode	*Capacity [tonnes]*	*Average Speed [km/h]*	*Price [€/(tonne*km)]*
Truck	45	70	0.038582
Ship	7000	37	0.018732
Train	1400	-	0.029194

4.4 Environment

The environment recreates the conditions and characteristics of the context in which the agents operate. In the case of a freight transport system, the environment refers to the physical properties of the goods (such as size or weight), the technological properties of the vehicles (such as capacity or speed), and the geographical characteristics of the region in question (for example, distance).

Using the taxonomy proposed by Russel and Norvig (2003) to describe the environment of an agent-based model, the environment of the model described herein exhibits the following properties: i) partially observable; ii) stochastic; iii) sequential; iv) static; v) discrete; and vi) multi-agent.

4.5 Interactions

As indicated in Section 4.2, transport agents may interact in two different ways. Each one is simulated in the model as follows:

- *Physical interaction* refers to the flow of cargo, particularly in the case of operations between Transport Service and Terminal.
- *Information interaction* refers to the exchange of information during the negotiation and management of the transport system, the central agent being the ITO or STO.

4.6 Decision-Making Process of the Operator Agents

4.6.1 *Order Priority*

During the planning or re-planning tasks, the Operator Agent is often confronted with the need to sort the orders for processing. The reasons for this are diverse, but include capacity restrictions or mix of orders (e.g.; new orders vs. delayed orders). The following rules were implemented in the simulation model:

1. **Delivery time:** The purpose of the Operator Agent is to ensure that all orders reach the destination within the stipulated time, so orders with an earlier delivery date will be a priority.
2. **Time Window:** For orders with the same delivery date, those with a pickup date closer to the delivery date offerless flexibility, so they are allocated first.
3. **Dimension:** Larger orders are more difficult to allocate, so they have fewer transport options in scheduled services; also, these benefit the most from the greater capacity of trains and ships, so they should take precedence in allocation to these modes.

4.6.2 *Itinerary Choice*

The choice of itineraries can be dividedintothreedifferent procedures: initial planning, re-planning, and review of transportation plan.

When the Operator Agent enters the initial planning state (the Plan Transport stage in Figure 3), orders are sorted according to the previously discussed priority criteria; then, the most adequate itinerary for each one is selected, according to the logic depicted in Figure 4. The decision-making process was based on the stepwise approach initially proposed by D'Este

(1996) for the case of tactical-operational level decisions. The tactical level refers to thosenot infrequentcases in which a decision-maker, typically a middle level manager, is required, multiple times a day, to organise a transport service in a short period of time (e.g., spot markets) and, oftentimes, with variable information. Due to the particularities of the synchromodal concept, the tactical and operational levels are blended together, with the logistic operator both organizing the use of resources within the supply-chain, and assigning orders to services.

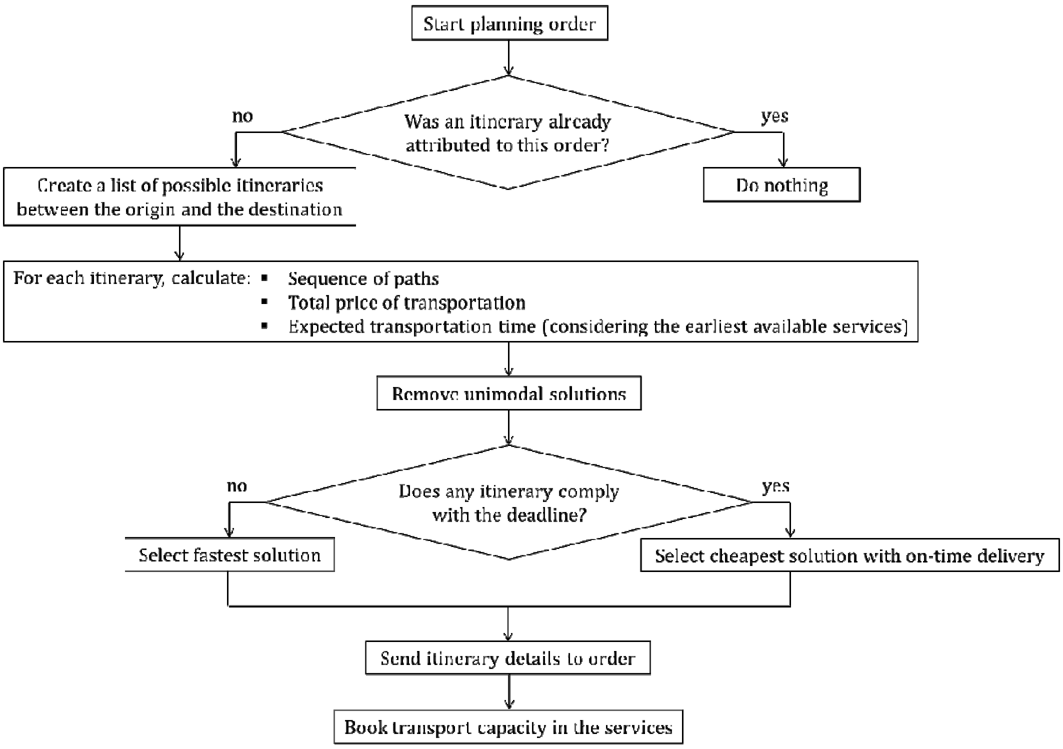

Figure 4: Decision-making process for the initial planning

When a disturbance occurs, the Operator will be forced to re-plan the transport, in order to accommodatethe new system conditions.

Up to this point, the ITO and STO Agents' behaviour is identical, as the initial planning process only requires knowledge onthe available transportation services. During the re-planning (occurring during the actual transport service), however, the extent of the Operator's knowledge ofthe conditions in the system, as well as itsresponsiveness, will determine its ability to mitigate the impacts of disturbances on the transport service. Since the main goal of this research work is to study the potential benefits of synchromodality in comparison to intermodality, the behaviours of the Operator Agents reflect the characteristics of each transportation concept.

During the re-planning, the ITO is constricted by the initially assigned itinerary.Thus, he may only re-schedule booked services for the remainder of the order's journey, proceeding in accordance with the following logic (Figure 5):

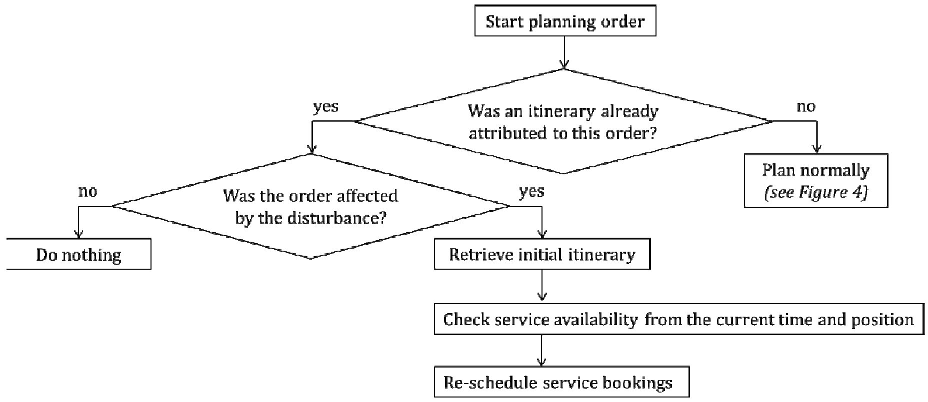

Figure 5: ITO's decision-making process during re-planning

The STO, on the other hand, is free to either re-schedule services, or even change the itinerary to a more suitable one. In addition, since ithas access to a fulleroverview and scopeof the system, itcan review the planning of unaffected orders; by monitoring these orders' transport, itmay find more advantageoustransport solutions that have become available due to the re-planning of other orders. This decision-making logic is illustrated in Figure 6.

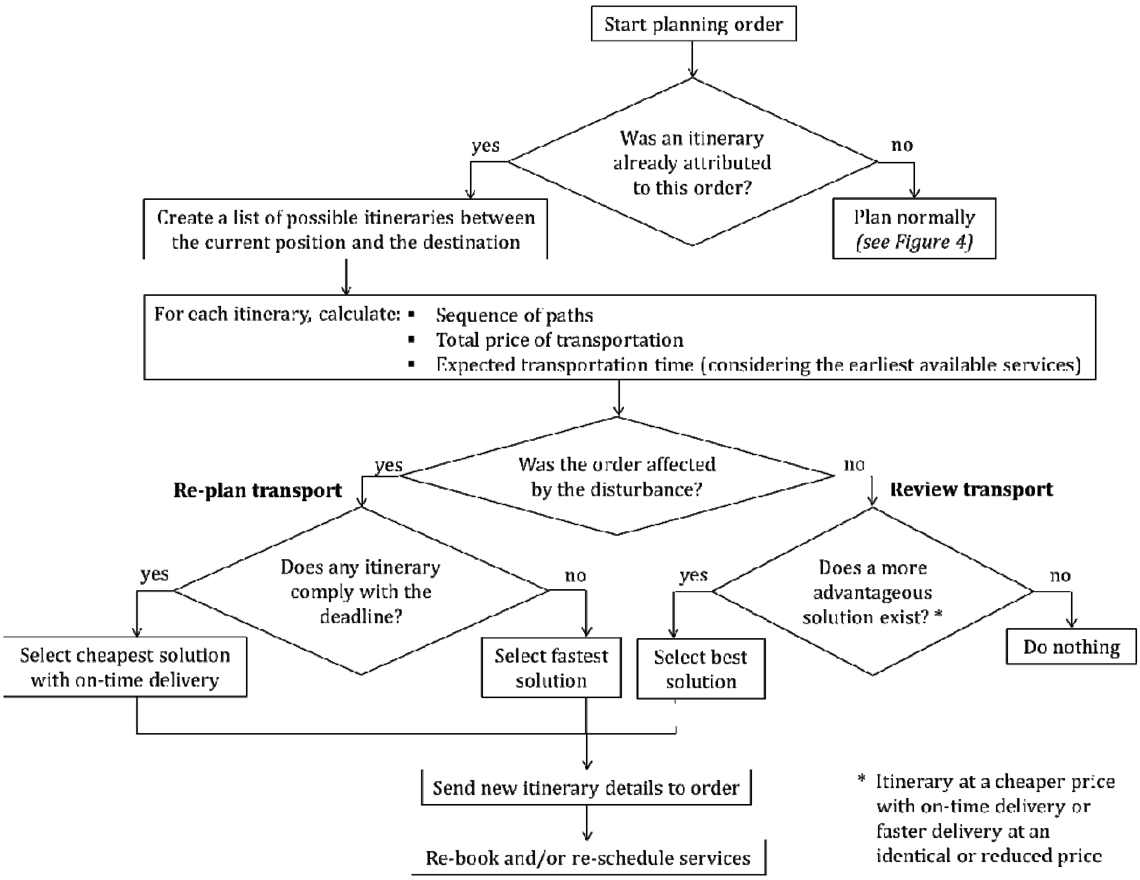

Figure 6: STO's decision-making process during re-planning

4.7 Verification and Validation

The difficulty in verifying and validating complex system models is recognised in the literature (Axtell, 2000; Sterman, 2004; North and Macal, 2007). Likewise, the literature is abundant as far as verification and validation recommendations are concerned.Following the suggestions available in the literature (e.g., Carson II, 2005; Castle & Crooks, 2006; North & Macal, 2007; Sterman, 2004), the verification process was executed continuously throughout the development of the model. With regard to validation, North and Macal (2007) proposed a set of validation steps to be performed, as follows:

- Requirement Validation: the model should meet clear requirements and respond to real-world issues.
  As discussed in Section 1, the developed model aims to simulate the transport chain's performance, as well as the behaviour of the agents operating in it, in order to serve as a tool for the validation of hypothetical scenarios.
- Data Validation: the data in the model should be valid.
  The model makes use of different sources of data, such as actual data from the field (e.g., routes, or vehicles' operational properties), other studies (e.g., transport service prices) and interviews with experts (e.g., train schedules) as discussed in Section 3.
- Theory Validation: the assumptions of the model should be valid.
  The assumptions (presented in Section 4.1) followed the conceptualisations of freight transport services and the modelling practices found in literature(discussed in Sections 1, 2 and 4.1), as well as the views transmitted by experts in the sector.
- Process Validation: agents and the interaction structure and steps in the model have to be clear, meaningful and correspond to the real-world processes.
  The developed model seeks to reflect the typical transportation processes, as well as the relevant object's real-world properties; its structure is based on previous work on the conceptualisation and modelling of freight transport services, as presented in Section 1 and 4.1.
- Agent Validation: agent behaviour, relationships and interactions have to correspond to real-world actions.
  The agent development was based on the descriptions, considerations, and concerns present in the consulted literature, as discussed in Sections 1 and 4.1.

5. Description of Experimentsand Discussion of Results

The developed model was tested for a set of experiments, depicting the capabilities of different types of Transport Operator, which were confronted with varying conditions in the supply chain. The present chapter describes the tested scenarios, and compares the obtained results.

5.1 Experiments

An experiment refers to a specific parametrisation of the model variables (described in the previous Section). Multiple experiments were designed to simulate different market conditions, their settings are presented below.

5.1.1 *Transport Operator Agents Types*

We considered one type of intermodal and two types of synchromodal Transport Operator Agents. Their key behavioural properties are:

- **Intermodal Transport Operator (ITO)** is a typical intermodal agent. When it receives a disturbancenotification, the ITO performs a re-scheduling of the affected orders, allocating them to the next available services, but without changing the itinerary.
- **Synchromodal Transport Operator 1 (STO 1)** is a hybrid concept between the previous (ITO)and the subsequent(STO2) concepts. This agent represents an STO Agent operating in a network where the technological capabilities do not yet allow for real-time monitoring of the network; such would be the case of a newly introduced service (still in an intermediary stage of evolution) that operates according to the synchromodal concept, but in which the technological requirements weren't fully implemented by the remaining agents. In these conditions, the STO 1 is reactive, only intervening in case of a disturbance, similarly to the ITO. When a disturbance occurs, the STO1 is instantly notified and will look for alternative transport solutions, which may include the re-scheduling of the affected orders (as in the ITO), or changing modes of transport and hiring other transport agents (as in the STO2).
- **Synchromodal Transport Operator 2 (STO 2)** is a full-fledged synchromodal agent. It is proactive, periodicallysearching for opportunities to improve the transport service, independent of whether a disturbance occurs or not.The STO2 will always scan the market for opportunities of improving the transport service, either through a re-scheduling or changing the mode of transport and hiring other transport agents.

5.1.2 *Scenario Design*

We considered five scenarios representing three distinctive market conditions (Table 6):

- **Base Scenario (B)** represents a typical freight transport market. The parameters were based on the collected data regarding the Atlantic Corridor, and chosen to represent the expected average conditions.
- **Time-window Scenarios (T1 and T2)** represent Customer Agents of different sensitiveness to transit time. Scenario T1 simulates time sensitive customers; while scenario T2 simulates non-time sensitive customers.
- **Responsiveness Scenarios (R1 and R2)** represent Transport Operator Agents – ITO and STO1 – with different levels of technological enhancementin terms of communication capabilities (e.g., track and trace). In particular, the scenarios define the time it takes to notifythe Transport Operator of an occurrence, and the time it takes to implement a decision. It should be noted that, by definition, the STO2 has constant and real-time communication with the other transport agents.

Table 6: Parameter variation in the simulation runs

Model parameters		*Base Case Scenario*	*Delivery Time Scenarios*		*Responsiveness Scenarios*	
		B	*T1*	*T2*	*R1*	*R2*
Simulation period		01/01/16 – 01/05/16 (2904 h)				
Order generation [hours]		Normal (6; 0.5)				
Customer's request in advance [days]		0.5 - 2	0 - 1	2 - 3	0.5 - 2	0.5 - 2
Customer's time-window delivery [days]		2 - 4	1 - 2	4 - 5	2 - 4	2 - 4
Notification delay (average) [hours]	*ITO*	2.5	2.5	2.5	1.5	4
	STO 1 and 2	Immediate	Immediate	Immediate	Immediate	Immediate
Implementation delay (average) [hours]	*ITO*	5.5	5.5	5.5	4	7
	STO 1	4	4	4	2	6
	STO 2	Immediate	Immediate	Immediate	Immediate	Immediate

5.2 Discussion of Results

Each experiment was run a sufficient number of times to satisfy normality conditions, and to fully capture the randomness of the model.The results provided a basis for comparing intermodal and synchromodal transport services.

For this comparison, we considered two performance variables, reflecting the concerns raised in the literature (Nabais, Negenborn and Botto, 2013; Spikker, 2014):

1. The price of the transport service supported by the Transport Operator Agent. Actual prices may differ from planned prices when the Operator Agent needs to introduce changes to the initial planning or compensate the Costumer Agent for any non-compliance (e.g., a delay).
2. On-time delivery. Actual transport time may differ from the planned transport time in case of delays, detours or other unexpected events.

The environmental impact of the transport solution is appointed as an important indicator of the supply chain's performance. In this study, the price of each transport mode considers a penalization for carbon emissions (as previously described in Section 4.3.4); thus, the concern for sustainability is present in all Transport Operator Agents' decision-making process.

5.2.1 *Price of Transport*

Results[5] are presented in Figure 7 (responsive nessand base scenarios), and Figure 8(time-window and base scenarios). Naturally, only variations in the STO Agents were recorded, as, by definition, the ITO operator does not change the initial transport contracts. Overall, minor variations in price were recorded,with final prices ranging from 96%to 101% of the planned prices. In the responsiveness scenarios (Figure 7), STO Agents were consistently able to reduce transportation prices;the time-window scenarios,however,present mixed results (Figure 8). In scenario T2 (less demanding), the STO Agents were able to findcheaper transport solutions. Conversely, slight increases in the prices were recorded for the T1 scenario (more demanding). This reflects the STO's decision-making process, discussed in Section 4.6, which favourscompliance with delivery time-windows over price reduction.

The results offer evidence as tothe potential of the synchromodal concept for reducing the overall planned price.Albeit, in this case, a rather limited extent (maximum gains below 4%).The limited gains can partially be explained due to the already high level of competitivenessinthe freight transport market, which leads transport agents to offer low prices in the bidding stage. Accordingly, any further reductions depend largely on casual market opportunities (e.g., empty truck returns).

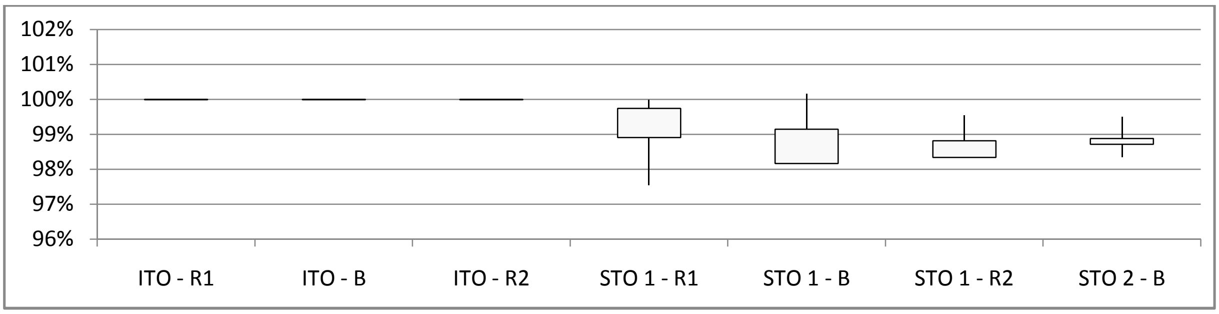

Figure 7: Ratio of real vs. planned transport prices – responsiveness scenarios (R1 and R2)

[5] Results are presented in a 96%-102% graph to better represent the distribution of results. Each result is characterised by four values: minimum, maximum, 1st quartile, and 3rd quartile.

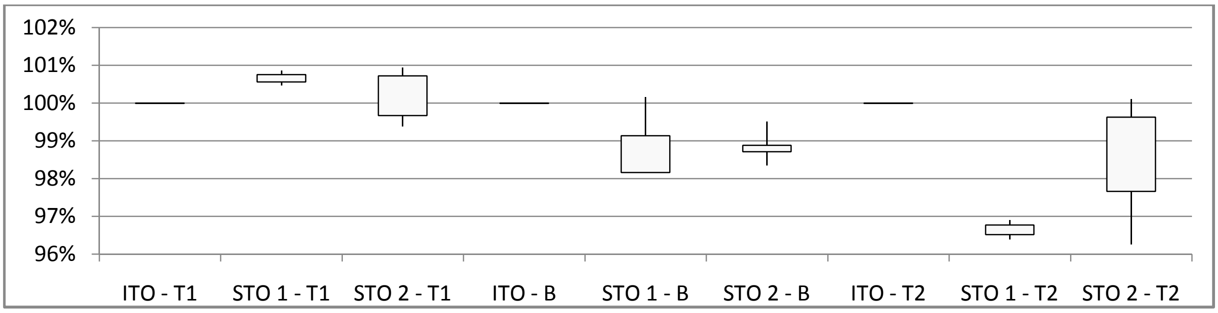

Figure 8:Ratio of actual vs. plannedtransportprices – time-window scenarios (T1 and T2)

5.2.2 *On-time Delivery*

In terms of compliance with the customers' delivery deadlines[6], the results for all scenarios are summarised in **Errore. L'origine riferimento non è stata trovata.**.The advantage of the synchromodal concept is clear and more evident than in the previous variable. In addition, the full-fledged synchromodal Agent (STO2) is the best performer in this respect. The STO1 Agent performs better than the ITO, although the improvement is limited. The results may support the interest of an intermodal transport agent in quickly evolving towards being a fully-fledged synchromodal Agent, although further research is needed.

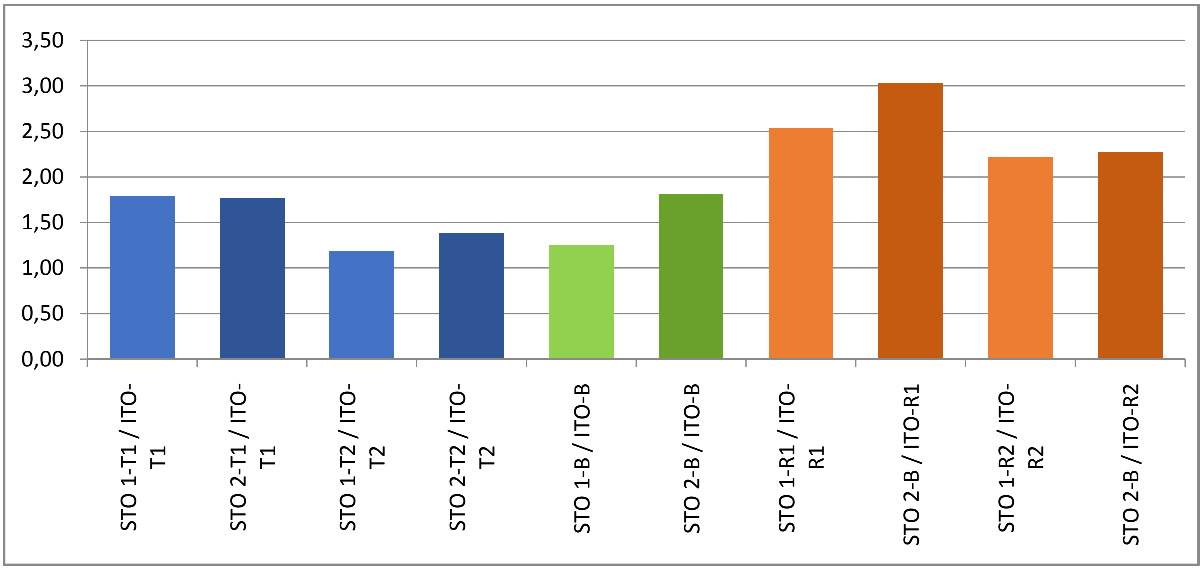

Figure 9: Ratio of the number of on-time delivery services

It may be observed that the advantage of synchromodality is not absolute, instead depending on the customer's requirements, as evidencedin delivery time and base scenarios – T1,B and T2. A decrease in the delivery time window increases the likelihood of a delay in a leg,resulting in a delay of the transport service. The synchromodal Transport Operator Agent, by actively seeking opportunities, is in a better position to offset the impacts of delays in the legs. Furthermore, the concept of real-time decision-making seems to be highly influential in terms of the advantage of synchromodality, as the greatest advantages were recorded in the responsiveness scenarios – R1. Hence, both the features of the supply chain and the capacity to quickly intervene seem to be highly relevant factors to the success of synchromodality.

[6] It is important to mention that we set demand as 100% of available capacity. However, owing to the randomness of the model, in some moments demand could be higher. In other experiments (not shown here) where demand was set differently and below 100%, we could observe similar results, but differences between scenarios were less expressive.

6. Conclusion

Synchromodality has gained inpopularity in recent years, largely fuelled by the promise of delivering enhanced multi-modal freight transport services. The distinguishing feature of this concept lies in the ability to freely change modes of transport, or transport agents, during the production of the transport service, based on real-time information. The implementation of this concept at the European Union level will require substantial changes in the transport sector (e.g., infrastructure, contracts and regulations, business processes and organisation, and technology).

Knowledge on this concept has grownas more literature is published; however, it remains limited, notably when comparing synchromodality against other more mature concepts.Further research is needed if we are to realise full exploitation of the concept's benefits. This manuscriptmakes several contributions to bridging this gap.

The first of these is the description of a new hybrid micro-simulation model of a freight transport market, where synchromodal transport services may occur. The market is populated with organisers of freight transport services (e.g., freight forwarders), which, according to the customers' requirements, hire on-demand transport agents. The organisers deliver intermodal or synchromodal transport services. The simulation model blends DES and ABM techniques:the former was used to simulate the process of the freight transport service; while the latter was used to simulatethe freight transport agents' behavioural properties and the geographical components of the market. An innovative feature of the proposed model is the new algorithm concerning the behaviour of synchromodal agents,which can be parametrised to simulate different responses and properties of the synchromodal transport agents.

The proposed model was calibrated to recreate the market conditions along the Atlantic Corridor of the TEN-T. A set of experiments was designed to assess the potential advantage of synchromodal transport vis-à-vis intermodal transport on this corridor. Of particular relevance was the definition of two types of synchromodal transport agents: one simulates a full-fledged synchromodal agent, while the other simulates an agent that is in an intermediate stage of development. We tested i) the influence of customer requirements, in terms of time sensitiveness, and ii) the influence of communication technologies, in terms of monitoring and reaction capability, on the potential performance advantage of synchromodal transport. Performance was assessed based on two variables: price of transport and on-time delivery.

The second contribution has to do with the conclusions that can be drawn from the results of the experiment analysis. The results revealed an advantage for the synchromodal concept, which was particularlyevident in the on-time delivery variable. Both synchromodal transport agents performed better; with the full-fledged agent exhibiting a clear competitive edge. In addition, results suggested that the added-value of the synchromodal concept is sensitive to customer requirements.

Results also evidenced the importance of technology, particularly communication,on exploitation of the benefits of synchromodality. In this sense, different levels of synchromodality (such as those we have tested with STO1 and STO2) can be envisaged. Applying the same reasoning to the other dimensions of synchromodality (e.g., contracts, infrastructure integration, etc.), one can conclude as to the likely existence of multiple levels and dimensions of synchromodality. Further research is required to develop taxonomies for the classification of synchromodality and, inherently, synchromodal agents. Additionally, one can hypothesise that each category could deliver specific benefits. If this holds true, the taxonomy could help agents to position themselves in the market. As far asthe price of transport variable is concerned, synchromodal transport can lead to an increase in the price of transport. An understandable outcome, since the synchromodal agent aiming at meeting delivery times (and, hence, complying with the contractual terms agreed with the customer) may be forced to opt for more expensive transport solutions. Furthermore, the transport price reductions are limited.

Nonetheless, they illustrate an important characteristic of synchromodality, which is the capacity to exploit unforeseen or casuistic opportunities (which is not the case for the intermodal concept).

Finally, the benefits of synchromodality appear to be linked to the characteristics of the supply chain itself. As networks grow more complex, the conflicts in the allocation of cargo are expected to increase, due to ahigher interaction between the transportation flows, as well as a greater competition for resources. On the other hand, opportunities for finding more suitable transport solutions (such as alternative modes, or routes) should also become more frequent. In these conditions, synchromodality may prove to be an asset in managing the flows within the network; conversely, one can envisage situations were synchromodal transport does not bring benefits.

This work illustrates but one of the many possible approaches to the study of Synchromodality and its potential as a transportation solution. In order to better understand the scope of synchromodality, further work should be developed with the aim of simulating its performance in more complex supply chains, with multiple corridors, or even hubs. The added costs of implementing Synchromodality should also be studied, in order to more accurately evaluate implementation trade-offs when comparing to other solutions. Finally, the schedule optimization problem could be added to the simulation approach, giving the STO the ability to negotiate service schedules with the carriers in order to meet changing transportation demands.

To sum up, the results support previous research conclusionsas to the added-value of synchromodal concept. Yet, it was also evident that full exploitation of its benefits depends on the fulfilment of(still unknown) specific conditions, not all of which are under the transport agents' direct control. Accordingly, more research is required, if we are to harness the full potential of synchromodality. In this manuscript, we have identifiedsome new avenues of research.

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