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Modeling logistic systems with an agent-based model and dynamic graphs

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A R T I C L E I N F O

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A B S T R A C T

This paper is about modeling and simulation of logistic systems. We define them as corridors established between a gateway port, where goods are imported, and urban areas, where the final distributors are located. The efficient management of the flow of goods operated on these corridors requires a structured territory and organized actors. Decentralized decisions of actors and interactions between them make it possible to provide consistent logistic services despite the numerous system constraints (legal, environmental, economical,...).

Our goal is to reproduce the behavior of logistic systems through simulation. Our approach consists of describing the dynamics of such a system at a micro level. Therefore, we first enumerate the local properties, constraints and behaviors of each main actor and the infrastructures of this territory in order to extract the essential elements that will be part of the theoretical model. A major aspect of the model is the description of the interface between maritime dynamics (schedule on a day-basis) and metropolitan dynamics (scheduled on an hour basis). This interface is self-organized: macro characteristics emerge from local properties and rules. It is revealing of a complex system, working on different scales, that we model with agents and dynamic graphs.

Each actor and infrastructure is represented with agents. The transportation network is a multi-modal dynamic graph that makes possible to model the traffic and topology evolution. This approach enables users, like public authorities, to modify local parameters and observe their effects at the macro level. Thus users can identify levers to control the whole system. We execute some simulations with data on the Seine axis to confront our results with a real case study. We provide some measures (*e.g.* number of vehicles and quantity of goods) to show that the simulation reproduces the atomization process of logistic flows. We propose a spatial analysis of the goods traffic within the transportation network and compare the effects of two replenishment strategies on the stock shortages.

1. Introduction

This paper provides a behavioral model of a logistic system to describe flows throughout its territory. We define logistic systems as corridors established between a gateway port (where goods are imported and exported) and an inland territory composed of interconnected urban areas (where goods are produced, transported and consumed). More precisely, this study concerns the arrival of goods through a gateway port and their removal to the inland territory, called the hinterland. The transportation network, connecting the port and its hinterland, integrates logistics activities in order to deliver the goods to the consumers according to the seven R's of logistics (right place, right time, right quantity, right quality, right price, right condition, right customer). So, actors of logistics (such as importers, exporters, transporters, logistics service providers, port authorities, forwarding agents, customs officers,...) have to organize themselves to satisfy the demand of these customers. The final goal of this work is to understand, at different levels, how a logistic system works; how actors dynamically structure and organize the flows within a territory thanks to decentralized decisions. Therefore, we were looking for a model able to simulate goods traffic within an organized territory and the interactions between the logistic actors.

Within the literature on the subject, we focused on models simulating goods traffic where many independent companies share a territory in order to cater to common regions. Some surveys (Tavasszy et al., 2001; Jin et al., 2005; Maurer, 2008) explain that the first works which studied this kind of models were inspired by passenger traffic models and used aggregated data such as SMILE (Strategic Model for Integrated Logistic Evaluations) (Tavasszy et al., 1998). These models mostly use aggregated data about the quantity of goods produced and consumed within a region and try to estimate the flow of goods between these regions. SMILE, in particular, considers some decisions about the

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consolidation of flows through distribution centers. Another model, proposed by Zondag et al. (2010), integrates the capacity to choose between different maritime ports. In both models, the evolution is made year after year. According to more recent surveys (Chow et al., 2010; de Jong et al., 2013; Taniguchi et al., 2014), models using disaggregated data appeared progressively in order to get results closer to reality. The FAME (Freight Activity Microsimulation Estimator) model (Samimi et al., 2010, 2014) is one of them. It has been designed to simulate the traffic between companies from the United States. The disaggregated data concern the characteristics of the companies, the multi-modal transportation network and the interactions between the companies. The authors of this model admit in a recent article (Samimi et al., 2014) that substantial efforts should be done in order to acquire all of these data and in particular in the case of another territory. Actually, this problem of data is often highlighted, as in Chow et al. (2010). Articles of Tavasszy et al. (2012) or de Jong et al. (2013) point out a lack of models able to manage the evolution in time of the system (*e.g.* its spatial characteristics or the topologies of logistic networks). According to them, future works should propose dynamic behaviors and interactions of the actors and a more detailed integration of port and hinterland logistics. Roorda et al. (2010) present a model with concepts of dynamics between actors, and applied to urban logistics thanks to the FREMIS (Freight Market Interactions Simulation) implementation (Cavalcante and Roorda, 2013). However, the authors explain that it is still a work in progress due to difficulties in getting necessary data.

This paper provides a model with a multi-scale and dynamic dimension of logistic systems, thanks to a complex system point of view. The entities of complex systems follow local rules which have overall effects at higher levels, like the territory itself. Henesey et al. (2003) tried this kind of approach concerning the terminals' community, and here, we want to apply the complex system approach to the port and its hinterland. The article tries to highlight why and how a logistic system is complex, and it provides tools to show its complex properties thanks to a simulation approach. Thus, the paper describes the modeling of a logistic system, including its actors and infrastructures, in order to assess the efficiency of the system, and how the initial configuration affects it. The model provides tools to analyze the complexity of the territory.

To design our model, the actors and the environment are first studied. It enables us to describe as accurately as possible the behavioral rules that could be integrated within the final model. So the paper highlights that logistic systems have characteristics revealing a complex adaptive system. We propose to decompose a logistic system into three different kinds of logistics: the port one, the urban one and an interface between them. The first is mostly characterized by large flows thanks to a massification process with container ships or bulk carriers. The logistic services on maritime lines are mostly standardized due to containers' dimensions. Moreover, ship arrival is on a daily basis due to schedule unreliability of maritime lines (Notteboom, 2006; Vernimmen et al., 2007; Nair et al., 2012). On the contrary, the urban logistics is characterized by "atomized" flows which are defined as numerous and small flows. The final consignees in urban areas expect very customizable services and the flows are mostly very punctual since deliveries are on an hour (and sometimes on a minute) basis. Between these two kinds of logistics, we propose the concept of interface which is a structured dynamic network of actors and infrastructures. Its goals are to atomize the flows, to provide the capacity to absorb the delivery difficulties of international transportation, and to provide numerous and customizable logistic services.

Then, it is explained how tools, such as agent-based approaches and the graph theory, are used to model these systems. We develop an agent-based model to represent the characteristics, behaviors and interactions of each actor and nodal infrastructure (such as terminals or distribution centers). We use dynamic graphs to represent the multi-modal transportation network in order to observe traffic evolution and give the capacity to update its topology dynamically.

Eventually, the implementation simulates the physical and information flows. The simulation is detailed thanks to many parameters. They represent particular aspects of reality (for instance, the location or the size of a warehouse) and they give control over the model. Indeed, they can be modified in order to see their impacts on the final results. Both individual behaviors and the numerous parameters can influence the different simulated scenarios to help decision makers.

2. The logistic systems

A territorial logistic system is constituted of a large set of actors and infrastructures. They are numerous and heterogeneous. At a micro level, they are strongly connected to each other in order to organize the transportation of goods through different infrastructures.

The first step of our methodology to design our model consists of listing most of the main aspects of logistic systems: their functional rules, the behaviors of each actor, the characteristics of infrastructures... Therefore, in the following section, although we do not provide innovative information for the reader, but instead, we gather together the detailed properties and functional rules of such a system in order to provide an overall view. Each aspect presented here helps to the design of our model and its implementation.

2.1. The actors and their roles

Firstly, the paper shows that the transportation of goods is organized by a mixing of diversified actors. Each of them is responsible for a part of the flow of goods. The next section explains the motivations and roles of these actors. Moreover, we mainly talk about the import case but it is often valid in the export direction.

2.1.1. Port logistics

A flow of goods is initiated from a partnership between an importer and a foreign goods provider. They estimate the final consumers' needs: what kinds of products they want, but also, when, where and which quantity. They draw up an international sales contract which defines who is the owner of the goods during transportation (called the *freighter*), and describes the product, the quantity, the prices, the delivery information.

According to the negotiated contract, the provider and the importer are respectively responsible for the goods. They can organize the transport themselves on their own section but in most cases, this complex work is subcontracted to a *freight forwarder* who becomes responsible for the goods on behalf of his customer. This actor contacts the *international transporter* and selects a *shipowner* and one of his shipping lines. He also deals with the *import and export custom duties*.

The shipowner and the freight forwarder are the two actors involved in establishing the maritime transport cost. It is based on the route, the volume and/or the weight of the goods. Some of the shipowners are also freight forwarders in order to get a better control over costs, routes and get a better management of empty containers (De Langen et al., 2013). Here, we can observe that some actors cumulate the roles: our model should also offer this possibility.

On the port side of a logistic system, the transportation of a product might be delayed. Different studies (Notteboom, 2006; Vernimmen et al., 2007; Nair et al., 2012), supported by Drewry Shipping Consultant or SeaIntel's reports, show the schedule unreliability of maritime lines. The logistics of the foreign goods provider could be a source of delays. But moreover, maritime traffic being a complex system itself, is difficult to predict. Vernimmen et al. (2007) explain that " between April and September 2006 (*i.e.* about 200 vessel calls per week), more than 40% of the vessels deployed on worldwide liner services arrived one or more days behind schedule".

2.1.2. Interface logistics

In this part of a logistic system, the main actor is the *logistics service* *provider* (LSP). His main goal is to provide freighter with solutions to help him enforce the required logistic activities of his transported products (transport, warehousing, packaging...) (Liu et al., 2014; Jayaram and Tan, 2010; Rodrigue, 2012). There are different kinds of LSPs according to the level of service integration they provide. But in this paper, it is not necessary to make such distinction. We assume that they provide at least a service of warehousing and of transportation. More precisely, a LSP uses a multi-level network of warehouses (see Section 2.2.3 for precisions about this infrastructure). This network is the physical support of the supply chain in the hinterland. A LSP selects warehouses to build the supplying network according to the different constraints (the logistic activities required by the goods, and those provided by the warehouses). Then, he operates goods within the warehouses, and also their relocation to well-balance the different stocks of goods between the nodes of the network. The way to build the network has an impact on the frequency of deliveries and the distance covered by the goods (which increase the final costs of transportation). Therefore, this actor needs to optimize the creation and the management of the network in order to reduce the logistic costs.

2.1.3. Urban logistics

At the end of this logistic corridor, there are shops and factories, spread over the territory, next to the main inhabited areas. The main issue associated to urban logistics is how to deliver goods in the last kilometer. The transportation network is often congested inside these areas and deliveries undergo specific operational constraints (*e.g.* deliver within short intervals).

Another issue is linked to the high real-estate costs in urban areas. The storage surface allocated locally might be very small due to these costs. Therefore, the risk to suffer from stock shortages is higher if the supply chain is not quick to react. It becomes necessary to outsource a part of these local stocks in one or several close warehouse(s) but outside the urban area. Due to the size of the storage surface allocated, the quantity of goods per transportation between the final consignee and the warehouse is low, but the frequency is high.

To summarize, on the urban side of a logistic system, importers must manipulate on-time flow of goods. And they must meet the demands of their final customers but they have limited local stocks. Thus, stocks must be replenished regularly to avoid suffering from stock shortages (lest they might lose some customers or stop manufacture). Moreover, these importers are numerous and spread over the different main urban areas. Thus, the flows of goods in urban areas are numerous but small. We say that these flows are atomized.

2.1.4. Logistics of the hinterland seen as an interface

We saw in the port logistics' section that when the goods enter the system through the port, the flow is massified and might be delayed. It highlights the interface problem between the massification and possible lateness on the maritime side, against the atomization and punctuality on the urban side. Actually, the LSP and his supplying network play the role of buffer zone[1] between the maritime logistics and the urban one. The outsourced local stocks make it possible to deliver the products quickly to the importers and to avoid some stocks shortages. Moreover, the size of the outsourced stocks and the logistic activities provided by the network's nodes allow some flexibility: if the goods' arrival is delayed because of the provider or the transport, the outsourced stocks will temporally ensure the importers' immediate needs. Nevertheless, to work properly, this buffer must be structured and organized by the LSP. He must select an efficient topology of the supplying network and an optimal geographical position to its nodes. Thus, the logistics of the hinterland is the *interface* between the port- and urban logistics. It is the heart of the atomization process of the overall flow of goods.

At the micro level, the auto-organization is due to interactions, rules and roles of actors constrained by the network, their own needs, and work habits. It leads to emergence of overall patterns at the macro-level. A first overall pattern is observed: actors collaborate with each other, forming local and strongly connected communities, such as the port community. The second one is revealed by the functioning of supply chains that generate logistic paths which match preferred flow supports. This multi-scale process is characteristic of the complexity of logistic systems.

2.2. Infrastructures and their functions

During transit, the goods go through different kinds of physical structures: nodal and linear infrastructures. Each of them has specific characteristics and functions studied in the following section.

2.2.1. Infrastructures of ports

Ships moving on maritime lines between ports can carry a huge amount of goods (up to around 20,000 TEU [2] for the largest container ships). It implies a massification of the flows and a reduction of the transport costs improving its competitiveness compared to other modes. However, ship arrivals are on a daily basis due to a lack of punctuality.

Maritime terminals are multi-modal infrastructures connecting maritime lines and other modes such as road, river and rail modes. Most of the goods are shipped in containers, except specific kinds (*e.g.* bulk goods or cars). Containers can be dwelt temporarily at the terminal even as it is expensive beyond a few days (Martín et al., 2014). We can also notice that the time to unload (or load) a ship depends on some parameters (Carlo et al., 2014) such as: the number and the characteristics of portainers, but also the number of containers to move before we can extract the one to unload.

2.2.2. Connections with the hinterland

The river lines provide the second most used mode after the road on the Seine axis as well as on many other corridors such as Antwerp. The river barges can carry large quantity of goods at the same time. It is the second most massified mode of transport, after the maritime one. Also, this transportation minimizes the carbon footprint and is considered as an ecological solution compared to other modes of transport to the hinterland. Moreover, it is considered as a secured way to transport valuable goods compared to road. Thus, the river lines can be very competitive even if their sphere of action is limited to the terminals of the river itself.

The rail freight stations are also multi-modal infrastructures and can be present in terminals or at some factories. However, grouping isolated wagons can be very complex to manage, and it is more frequent to operate directly full trains (for instance, to transport new cars at the exit of a factory). The quantity of goods transported per train is less than the one transported per river barge, nevertheless, it is still an attractive mode of transport since the rail network is more dense than the river one.

The road network has the particularity to be connected to every nodal infrastructure of a logistic system. Thus a truck can carry a container all over the territory to any infrastructure. However the vehicles on the road network can only carry a small quantity of goods, and the financial and carbon costs are not so competitive. Yet this mode of transport is the most used on hinterlands. The advantages of the road network, such as its flexibility, still make it very attractive.

On the hinterland, the modes of transport provide definite delivery times (in particular the rail and road freight). So it is possible to predict the arrival date precisely.

[1] In computer science, the term *"buffer zone"* designates a memory area used to store temporarily the data exchanged between two processes or devices which have not the same transfer capacities.

[2] Twenty-foot Equivalent Unit.

2.2.3. Infrastructures of supplying network

The nodal infrastructures of the hinterland are the warehouses, distribution centers and logistic platforms, gathered into one and the same term: logistic places. A warehouse is the most simple infrastructure. It just receives products, stores them, and processes the orders. Its goal is to outsource the stocks of other places, *e.g.* a shop or a factory. This kind of infrastructure provides a static storage (more than 24 h). It might be associated with only one other place or company, and so it differs from the distribution centers. This second infrastructure is a particular warehouse, specialized in the distribution of products to other infrastructures. It integrates more sophisticated logistic activities than a warehouse, such as deconsolidation or cross-docking. The distribution centers are also more dynamic: the goods are not necessarily stored inside racks, they might be just processed and then leave the center. Eventually, the logistic platforms, strongly dynamic, provide the highest level of integration of logistic activities. They might be multimodal, they provide a large set of different logistic activities, and it is not rare to see them run by several distinct operators.

A LSP, who manages one or several of these logistic places, may procure some logistic activities (Stefansson et al., 2006; Rodrigue, 2012; Gavaud et al., 2009), such as, but not exclusively:

- Consolidation /deconsolidation: the consolidation process consists of building a larger outbound flow from many smaller inbound flows of different origins but of identical destination. The deconsolidation is the opposite process.
- Cross-docking: it is a practice where the goods from the inbound flows are not stored, but directly reorganized in order to build outbound flows. It is often used in retail logistics and mailing. It can be used to change the transport mode, or to sort the goods coming from the different inbound flows and going to different destinations.
- Container stuffing/unstuffing: to take in (stuffing) or take out (unstuffing) goods of a container.
- Quality control: to check if the goods are in good condition (edible food, object not broken, textile not torn,...).
- Repackaging: to make a particular process to the goods such as: packaging, labeling, smoothing out,...
- Order preparing: to place the right product, in the right quantity, in the right vehicle at the right time according to an order.

The LSP must organize the supplying network according to particular criteria (Stefansson et al., 2006; Gavaud et al., 2009) because of product constraints (like food or chemical products), or because of efficiency constraints. Therefore, the LSP must create and manage a complex network of logistics places in which he satisfies the product constraints and optimizes the logistic costs (Rodrigue et al., 2013; Gavaud et al., 2009). Figs. 1 and 2 are representations of how to organize and build this network. The first one describes how the LSP might find an appropriate location for his infrastructures in order to minimize the distance covered by the goods (and therefore the costs) and the time of transportation (improving reactivity). Fig. 2 shows how the network is organized as a multi-level network, which enables the LSP to optimize the atomization or the massification of flows (Gavaud et al., 2009). The reader can notice that these two configurations are symmetrical. The join network is used for the exportation in order to group the flows, while the fork network is used for the import to atomize the flows.

Fig. 3 sums up the main elements of the two previous sections about the actors and the infrastructures. We can see that the flow goes through different infrastructures following routes over the system, and obeying organizational patterns. The figure represents a classic route, but it might be more sophisticated according to the constraints applied to the transported products, and also the constraints or work habits of the studied logistic system. Each specialized actor manages just part of the flow. There is no main authority who is in total control. The process behind the organization of the flow is decentralized. Actors need to collaborate, or simply work together to build a flow, consistent with the constraints of products and the territory entail. The observed patterns of this organization emerge from local behaviors and interactions of the system. Once again, it is revealing of the complexity of logistic systems.

2.3. Characteristics of the products

The goods are very heterogeneous. There are numerous and diversified products and their characteristics can entail particular organizations of the supply chain. This diversity contributes to the complexity of the whole system. Thus, it is important to describe their different aspects.

First of all, the goods occupy a volume and have a weight. These two characteristics are used to calculate the costs of transportation and storage. Then, some particular products need to undergo special treatment like frozen foods which need to be carried within reefer containers; textile which can be transported creased and be ironed once on the hinterland. Besides, specific goods cannot be stored within the same container or warehouse (*e.g.* food, wastes, chemicals or textiles).

The way to consume a product can also affect the supply chain. Some products have an expiry date, so, these products must be sold before this date. Sometimes, instead of an expiry date, we can consider the product's obsolescence: the older the product, the less easily it is sold. Finally, each product has a consumption frequency: some products are regularly consumed (for instance coffee), and on the contrary, some products are seasonal (like toys before Christmas).

In reality, the actors must think about these characteristics before they make decisions. Therefore, in our model, we should think about a way to model the goods, and how the actors and infrastructures can manage them.

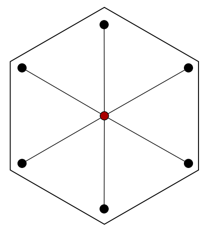
2.4. The complexity of logistic systems

This previous section described logistic systems and actually they share numerous characteristics with complex systems. Indeed, there is a high number of actors and infrastructures, and both are heterogeneous. Even two actors doing the same kind of job may work differently. The nature of interactions between the actors (and also between actors and environment) is also varied. Decisions are made locally, at a micro level, by autonomous actors and according to interactions. At a macro level, the actors and the different flows (of goods, of information,...) are organized according to some patterns. Some of these organizations are known: for instance, there are clusters of actors or infrastructures, such as the port community. There are also some regions where the logistic activities are really higher than elsewhere (Démare et al., 2016). The most important flows of goods follow specific routes through main itineraries. If we only observe the system at a micro level, we cannot envisage the existence of these organizations. According to complexity theory, the local properties of the system, the interactions, and the autonomous behaviors of actors are at the origin of the emergence of these macro organizations.

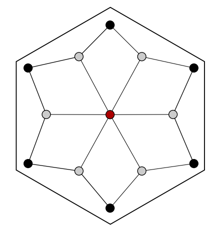
At this point, we consider logistic systems as complex systems in order to provide a multi-scaled model. This approach should allow us to understand how macro organizations emerge, and to facilitate the discovery of other organizations. Such a model is also the occasion to provide a decision support system thanks to simulation.

3. The conceptual model

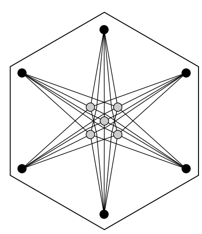
The previous section showed that we consider logistic systems as complex. Such a system and its characteristics can be modeled by well-adapted tools such as agent-based models (Ferber, 1999). Moreover, the dynamics of transportation network can be described thanks to graph theory. These tools can highlight the interactions between the components of a system (here the actors and infrastructures) but also its spatial dimension.



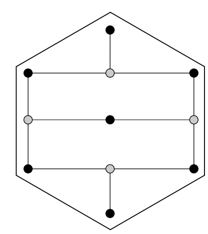
(a) Concentrated or centralized logistics: a non specialized logistic place (in red) is near the barycenter of the delivery areas (in black) (Gavaud et al., 2009). The logistic place has a dominant location in the space (Rodrigue et al., 2013).



(b) Decentralized logistics: even if there is a logistic place at the center of the area (in red), there are also sub-centers (in gray) (Rodrigue et al., 2013). These sub-centers might be specialized or not.



(c) Clustered logistics: many specialized logistic places (in gray) are near the barycenter of the delivery areas (in black) (Gavaud et al., 2009).



(d) Distributed logistics: many specialized logistic places (in gray) are distributed homogeneously over the territory (delivery areas in black) (Gavaud et al., 2009). None of the logistic places has a superiority over the others (Rodrigue et al., 2013).

Fig. 1. Representation of different spatial organizations of logistic places (such as warehouses, distribution centers or logistic platforms).

Before explaining our model, the next section studies the tools used, *i.e.* the agent-based models and the concepts of dynamic graphs.

3.1. Definitions of agents and dynamic graphs

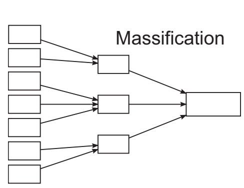
3.1.1. Agents

The agent-based models come from individual centered based approaches and decentralized methods (Von Neumann, 1966; Reynolds, 1987; Colorni et al., 1992). They appeared in the 1990s thanks to researchers like Gilbert and Doran (1994), Gilbert and Troitzsch (2005) or Wooldridge and Jennings (1994, 1995). These approaches consist of modeling the components of a system as independent entities. According to Ferber (1999), these entities called agents can model everything we want, such as individuals or a whole country. They can represent physical or virtual entities, but above all, agents are autonomous. The agents possess their own internal properties, behaviors and capacities. An agent has the ability to perceive and/or to manipulate its environment but also to interact with other agents. At last, the environment the agents are located in, has a topology (such as a continuous surface, a graph,...) and has objects which are not necessarily agents (for instance, a wall). This approach favors the addition of the spatial dimension of a modeled system and therefore its geographic data.

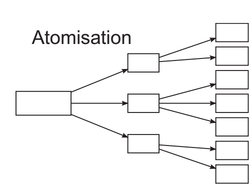
Agent-based approaches allow to model the diversity of the studied system thanks to many agents, but also many interactions between the agents. Moreover, agents can be heterogeneous: they can have different internal behaviors and properties, and therefore, they can interact in different ways. In this case, each kind of agent belongs to a *species*. It allows to describe complex systems with heterogeneous components (like, in our context, the different actors and infrastructures).

Agent-based models provide a fine granularity of representation at an individual level. It allows us to take control over the system and get different modalities of actions. The agent-based approaches can be detailed and configurable in order to achieve a sensitivity analysis for each parameter (the types of actors, their initial locations on the territory,...). Thus the modeled system is made sensible to local or global rules defined by the user who can therefore use this kind of model to help the decision process of land planning.

The review of Davidsson et al. (2005) shows that this approach has been used efficiently in a large number of scientific works about



(a) Logistic places in a join network



(b) Logistic places in a fork network

Fig. 2. The two main network topologies of logistic places.

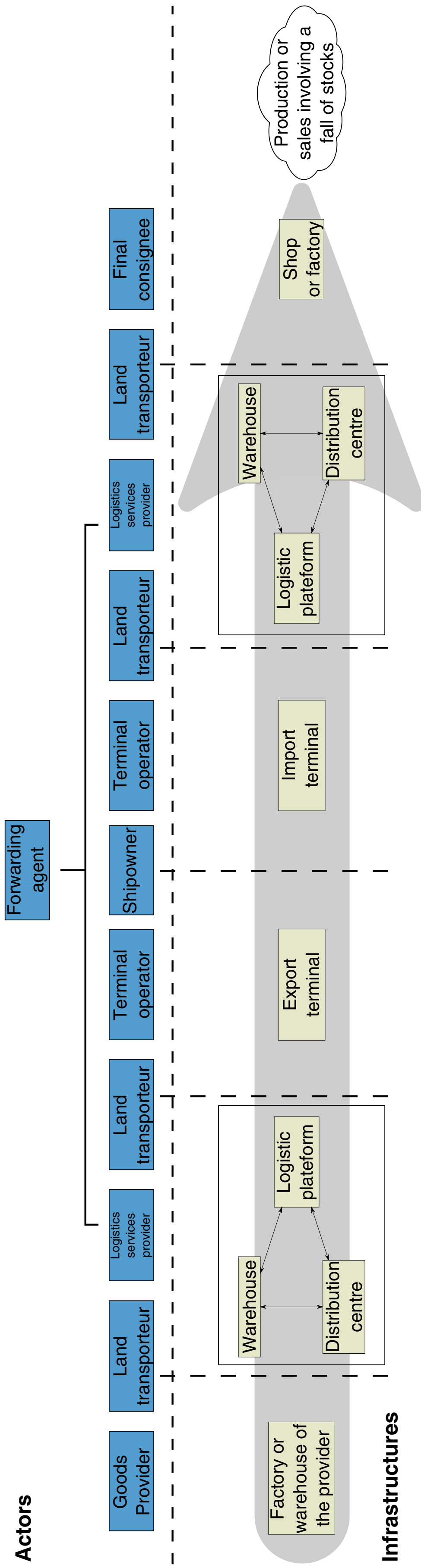


Fig. 3. Flow of goods over infrastructures and the actors that manage them.

logistics (Swaminathan et al., 1998; Funk et al., 1998; Henesey et al., 2003; Goldsmith et al., 1998; Hernandez et al., 2001) and more recent works continue to be published (Reis, 2014; Yuan et al., 2013; Holmgren et al., 2012; Giannakis and Louis, 2011; Hiel et al., 2011).

3.1.2. Dynamic graphs

Classically a graph is a mathematical structure defined as a couple of sets of vertices and edges (Gross and Yellen, 2005; Newman, 2010). It represents the connections (the edges) between some elements (the vertices, also called nodes). In this section, graphs are used on the one hand to model the interactions between the actors/agents, and on the other hand to represent the transportation network. However both integrate a notion of dynamics. For instance an agent is not always in interaction with another one. Thus sometimes an edge exists between these two actors, and sometimes it does not. Regarding the transportation network, there is not always the same amount of goods on a road: it changes over time. Accidents could happen at any time and also anywhere. Yet a classical definition of a graph cannot provide this dynamical dimension. Therefore the modeling of graphs must be adapted.

Many previous papers studied the modeling of dynamic graphs such as Ferreira (2002) and its *evolving graph*, Demetrescu and Italiano (2001, 2007) and its *graph by events*, or Cortes et al. (2003) and its *cumulative graph*. It appears that the dynamic can be defined sequentially in a discrete time (a graph is associated to each step of the discrete interval), and a node or an edge might only exist at specific steps.

Savin (2014) described a model where the dynamic concerns both topologies and data on the nodes and edges. Firstly, a graph integrates two functions that associate a key and an element of the graph to a value, and there is no restriction to the number of keys. Thus a graph has elements that can contain more than one value. However it is not enough to capture the dynamic. Therefore secondly, Savin defines a dynamic graph as a flow of events generated by a process which can implement events iteratively from an initial graph in order to ensure its evolution sequentially. These events can be the addition or the deletion of an element of the graph, but it can also be the modification of the value of an element.

This way to model a dynamic graph has been implemented in the Graphstream library (Dutot et al., 2008). Thus, it is possible to connect the implementation of the agent-based model with this library and analyze the graphs with the set of algorithms provided by Graphstream.

3.2. Modeling

The previous section about the logistic systems identified its key elements. This section presents the modeling of the most essential elements thanks to an agent-based approach. It is coupled with graphs which can represent either the network of interactions between the actors, or the transportation networks.

Agent-based approaches help to model the behaviors of the actors and the communications between them. Each independent agent makes autonomous decisions according to its perceptions of its environment and its interactions with other agents. It gives dynamics to this auto-organized system. Moreover, it brings a sufficient modularity to make the model's evolution possible.

3.2.1. Infrastructures modeled by agents

The environment is made of an overall network which is itself made of nodal infrastructures and specialized sub-networks (the maritime lines and the road, rail and river networks). The nodal infrastructures are agents connected to one or several sub-networks. Their function is to process goods. For instance, some of them, such as terminals, can allow the transfer of goods from a sub-network to another; some others manage warehousing activities… In each case, they broadcast the kind of logistics activities they can provide. But they have limitations: their surface of course, but they also have a maximal capacity to process a

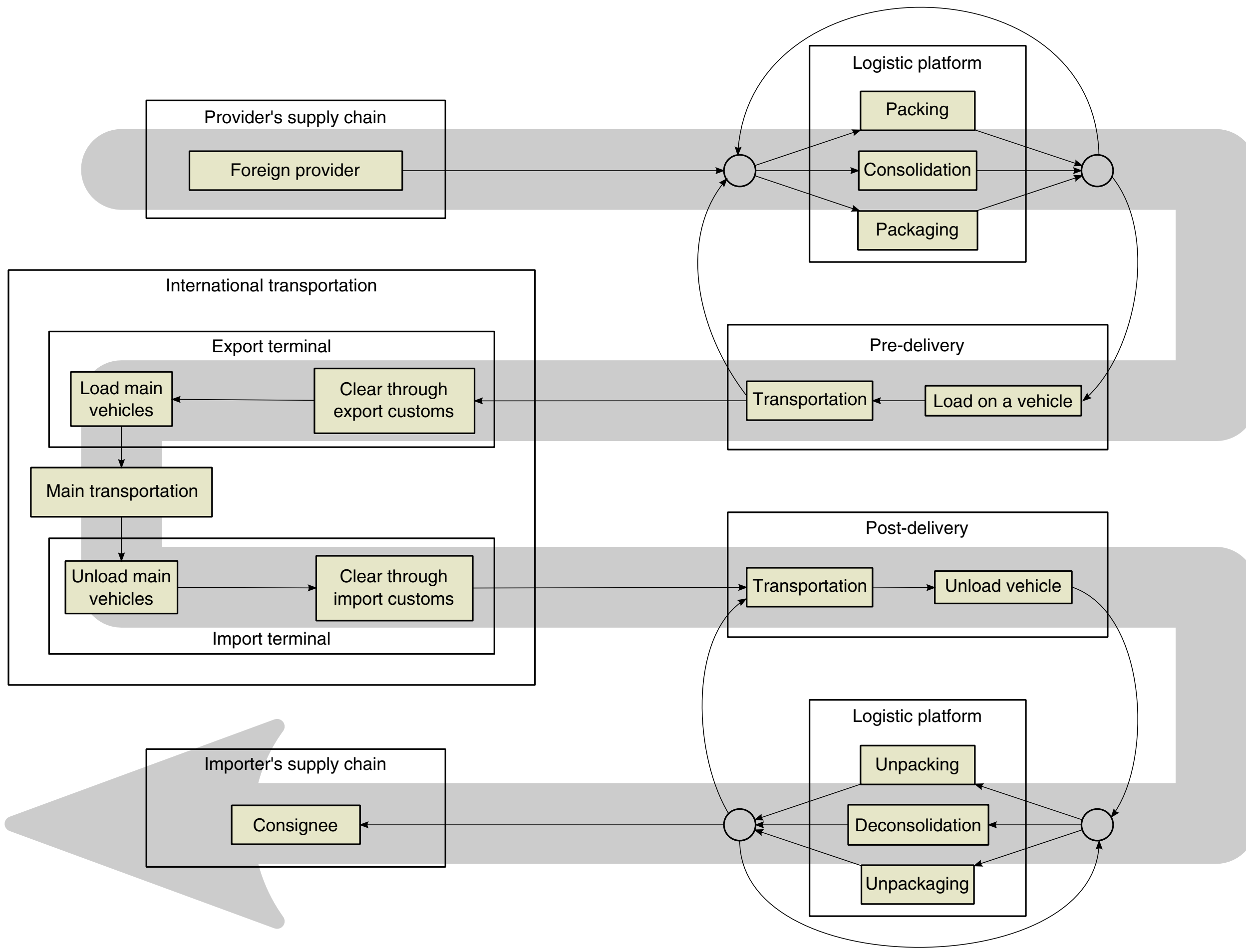


Fig. 4. Simplified representation of the different steps followed by containerized goods during the international transportation.

specific amount of goods per time unit. Each sub-network has particular characteristics such as maximum speed or the volume that can be carried with one vehicle. The overall transport network is a dynamic graph since the flows going through it can evolve and cause traffic jam. Moreover, the network can get new roads, suffer from accidents or roadworks. The modeled system must and can adapt itself to this dynamic.

The nodal infrastructures are included in supply chains in which the goods must follow each step as on Fig. 4. Each supplying network is the outcome of actors-agents' decision making and can change in time. Here the supply chains' graphs are clearly dynamic.

3.2.2. *Actors modeled by agents*

In Fig. 5, we model the main actors described in the previous section. One real actor is therefore modeled by an agent which belongs to one of these species (see Section 3.1.1). The figure shows how each agent might or must interact with other agents. The person in charge of the shop or the factory is the final consignee in this system. If the agent represents a factory, his place might be directly linked to rail network. He has local stocks of products which decrease due to sales or production. He must select a LSP who has the responsibility to provide his necessary logistics activities, in particular warehousing. A LSP agent designs a supplying network which satisfy the constraints of the final consignee's products. The topology of this network depends on the kind of product, and also on the preferred mode of transport. For instance, he can decide to transport food with trucks through a short circuit, with only one warehouse. On the contrary, he can decide to transport electronic devices with river barges and trucks through a long-circuit, composed of terminals and warehouses. The way to select a nodal infrastructure instead of another (when they both provide the same activities) depends on the strategies adopted by the agent (*e.g.* selections based on the size, distance, accessibility... of an infrastructure). Two agents of the same species may adopt different strategies. The LSP manages and well-balances the stocks in the nodal infrastructures of its network. If the stocks in the supplying network are too low, the import manager must negotiate the buying of products with a goods provider. Then they transfer the responsibilities of the transportation to a freight forwarder. The latter organizes the management of the goods with an international transporter and inland transporters until the goods reach a node in the supplying network. The movement of goods between the supplying network infrastructures is organized by the LSP. The inland transporters are specialized in modes of transportation. River transporters schedule departures regularly between maritime terminals and inland river terminals. Rail transporters are able to group isolated wagons. Like river transporters, they schedule regular departures between rail freight stations. For both these transporters first the goods must arrive at the terminal or the rail freight station before the river barge or the train departure, otherwise, the goods wait for the next one; secondly, the fuller the barge or the train is when it leaves, the lower the transportation costs per goods unit are. We assume that road transporters may deliver anywhere in the system, and the departure of trucks is immediate. Their transportation costs per goods unit are always the same. Trains, river barges and trucks cannot transport more goods than their maximal capacities.

The interactions that really occurred during the system evolution, are modeled in a partnership network by edges between the interacting agents. This network is of course a dynamic graph because agents may switch partners. At regular intervals of time, agents estimate the

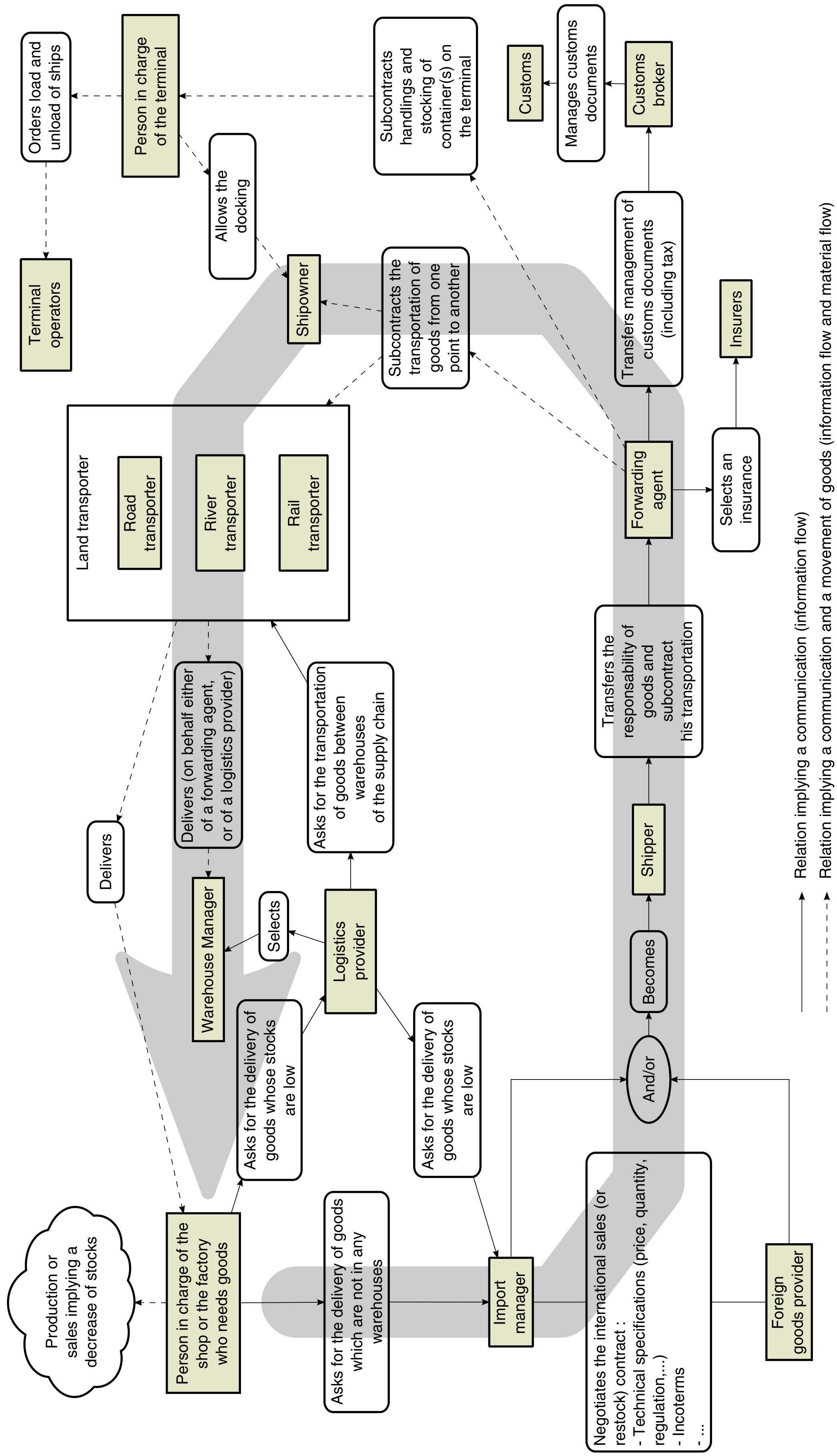


Fig. 5. Graph representation of possible interactions between agents.

efficiency of their partners. The user defines this interval: for instance, once a day or a month. The efficiency can be measured thanks to different indicators such as financial costs, the number of stock shortages, or reactivity (like the time needed to deliver a product). It is the user who decides which efficiency measure should be used. For instance, a final consignee can measure his number of stock shortages each day to assess the efficiency of his LSP. If a partner is not efficient enough (according to the method used to measure his performance), an agent can decide to select another partner. To come back to the example, if the average number of stock shortages of the last month is higher than its maximum accepted value, then the final consignee will decide to switch his LSP. In this case, the maximum accepted value could be the average efficiency measure of each LSP.

Since the strategies adopted by the agents are not the same, some of these strategies will be less efficient according to the efficiency measure used. For instance, a final consignee might use the total transportation costs of the last year as an efficiency measure of his LSP. The replenishment strategy of a first LSP might be to order a replenishment each day, even if the stocks are still high. And a second strategy might be to order the replenishment only if the stocks are under a threshold. In the second case, the transportation costs should be lower after a long period and therefore this strategy will be considered as more efficient. Agents who adopted these low efficiency strategies will have a high probability to lose most or all their partnerships. Conversely, agents who adopted high efficiency strategies are more likely to keep their partnerships. Therefore, the model should converge toward the adoption of the most efficient strategies. According to the efficiency measures used and the set of possible strategies, optimal organizations should appear progressively. Since the model is dynamic, if the system is disrupted by an event and if the most efficient strategy so far becomes suddenly less efficient than a second one, then the agents will adapt their behaviors and will adopt this second strategy progressively.

The species an actor belongs to determines how it can interact with other agents, but also with the environment. Indeed, the behaviors and decisions of some of them, such as the transporters or the LSPs, have an impact on this environment. They can increase or decrease the flows of goods on particular areas and therefore they influence the traffic's congestion or the stocks in warehouses. Conversely, thanks to information provided by the environment (for instance traffic congestion or the closing of a road), they can update their decisions in real-time (for instance the route taken by the goods). Therefore, there is a retro-action mechanism from the environment to the agents. Thus, both can interact (directly or not) with one another.

4. The simulation

In order to experiment the conceptual model, it has been implemented into a simulation platform. To achieve this, we only keep the essential aspects of the model. The simulation draws attention to the physical and information flows, but it could be possible to develop another simulation focused on the financial flows. The simulation must be as close as possible to reality to help the decision process of land planning. The implementation is studied in this section and the first encouraging results are discussed.

4.1. The case study of the Seine axis

In Europe, but not only there, there are many examples of configurations linking a port system and a set of urban areas as shown in Fig. 6. It is the case with the couple made by the Thames and greater London, or by the Benelux ports and the Rhine hinterland. We might also mention the ports of the Heligoland bight connected to the large cities of central and eastern Europe. The simulation presented here is the adaptation of the generic model to the particular logistic system of the Seine axis. Nevertheless this simulation can be applied to these other systems provided some modifications are made according to the geographical or political constraints of the chosen corridor.

The Seine river draws a natural corridor from the international port of Le Havre to Paris region (see Fig. 7). The latter city is the most important urban area included in this geographical space with around 11 million inhabitants. The Seine axis territory includes other urban areas such as Rouen, Caen or Orléans. All these main cities offer a high population density but also a large number of logistic actitivities. Therefore they attract and generate important flows of goods. The territory borders are delimited by the closest departments of the Seine. The whole region welcomes around 15 million inhabitants[3].

The road is by far the most used transportation mode along the Seine axis. Therefore the simulation does not implement a multi-modal network yet. Only the road network is functional. We have also grouped the warehouses, distribution centers and logistics platform under the same kind of agent, simply called warehouse. Indeed to begin with, we are more interested in movement of goods than the logistics activities within these infrastructures.

For the moment, the simulation works with real data of a Geographic Information System on the Seine axis, managed by the Devport project[4]. The final consignee agents are located thanks to data about real wholesalers on the territory, which also provide their local surface. The information about warehouses comes from a database of building permit between 1980 and 2011 of buildings whose surface over $2000m^2$. Thanks to these data, we know the storage surface of each building. Unfortunately, we have no idea of their volume. Therefore we must consider the square meter as a unit for the space occupied by the goods. This unit is used inside the buildings, but also inside the vehicle agents. The simulation is not focused on a particular kind of product, and we just need to have an idea of the fullness or emptiness of the stocks. However, we could easily adapt the simulation, and integrate a volume unit, if we decide to use a particular product whose characteristics are known. The road network dataset corresponds to the most important roads of the Seine axis (including highways, and national or regional roads). Eventually, the data about the LSPs have been collected by the Devport team itself. Of course, it is important to note that the simulation is not dependent on these data. It is possible to set the input data or play with the parameters. For instance, the simulation can work on a subset in order to study the evolution of a particular economic sector (such as perfume or textile). On the contrary, new actors can be added and the territory be extended to France as a whole (if the computer's performances allow it). Moreover, if there is another set of data, it is possible to work on a completely different corridor such as the hinterland of Antwerp.

We choose the GAMA Platform (Taillandier et al., 2012) as multi-agent simulation platform because it is specifically designed to integrate data from Geographic Information Systems. It is particularly appropriate to our needs as different surveys on agent simulation platforms (Railsback et al., 2006; Allan, 2010; Kravari and Bassiliades, 2015) show.

4.2. The methodology to implement the model

In this section we will describe the implementation more precisely. We will start with a description of the main agents: the “goods provider”, the “warehouses”, the “LSPs” and the “final consignees”. First, the goods provider is unique because he aggregates all real foreign goods providers. He is able to meet all kinds of requests in any quantity and for any kind of goods. Secondly, there are around 3000 warehouse

[3] Source (consulted September 25th, 2014): http://www.insee.fr/fr/ppp/bases-de-donnees/recensement/populations-legales/france-departements.asp?annee=2011INSEE (Institut National de la Statistique et des Etudes Economiques) - Legal population of 2011 of each French departments.

[4] A multidisciplinary research team who works on the study of the logistic system of the Seine axis in order to get a better understanding of its actors and infrastructures. Its website: http://www.projet-devport.fr/en/.

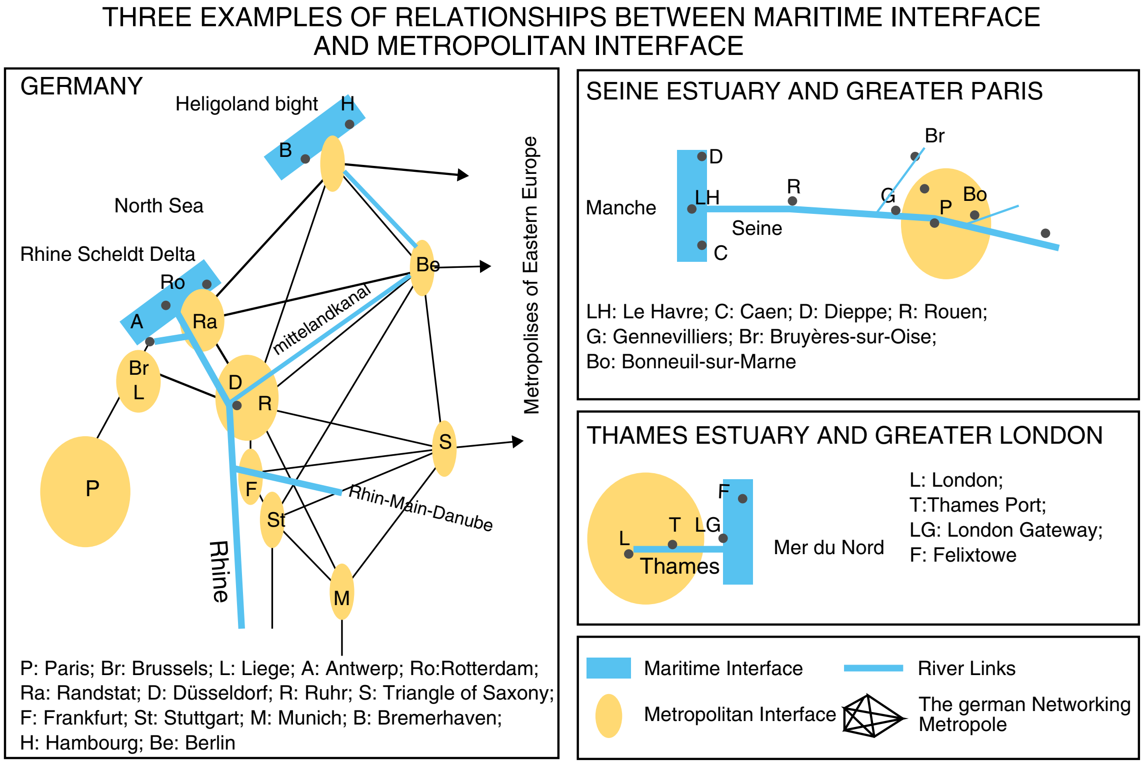
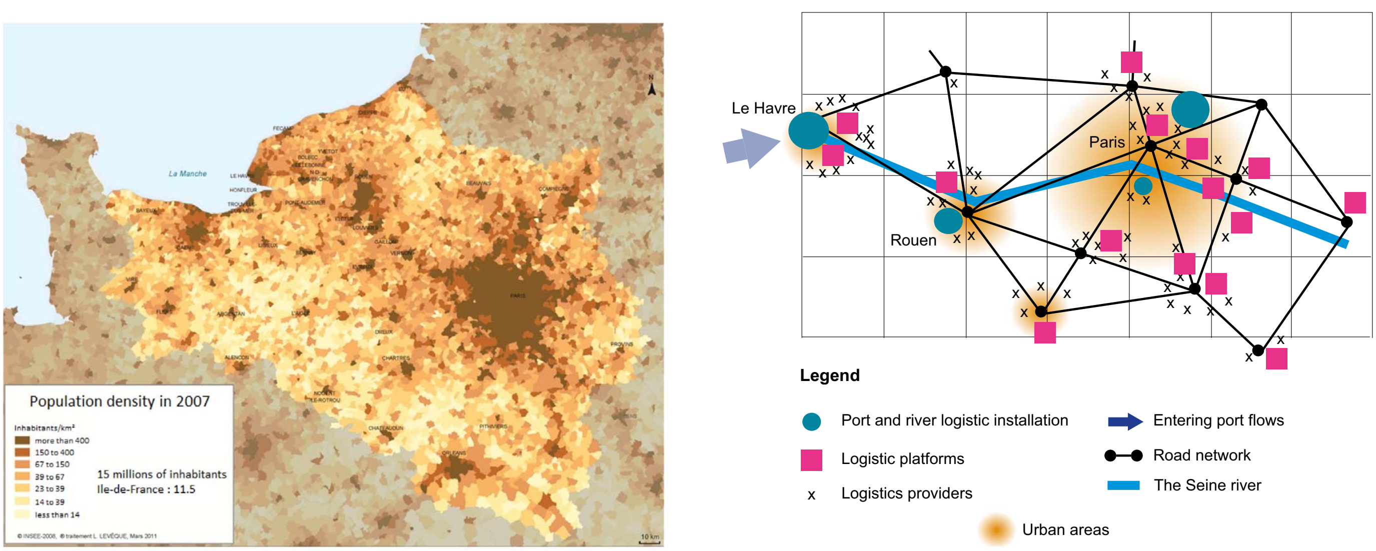


Fig. 6. Three examples of relationships between maritime interface and metropolitan interface.



(a) The population densities

(b) An oversimplified representation of the Seine axis and its actors and infrastructures

Fig. 7. The Seine axis territory.

agents and each of them may supply different surfaces. They receive and execute orders to send goods to another place. Thirdly, each final consignee plays the role of a retailer or a manufacturer. There are around 7700 of these agents. They have local stocks which decrease once a day because of sales or uses. The removed quantity corresponds to a random number, biased according to the estimated number of customers (computed thanks to Huff (1964)'s model). The management of replenishments is transferred to a LSP agent. Each final consignee has one LSP (the reverse is not true). There are around 2250 LSP agents.

This third and final agent has the main task to deliver quickly and in the right quantity the goods to his customers. To do so, he selects and manages warehouses of a supplying network. This network is created when the agent gets his first customer but may be updated when he gains or loses customers. The network is organized as a fork network (see Fig. 2): the goods provider agent is connected to one or several national-level warehouses; each national-level warehouse is connected to one or several local-level warehouses; and each local-level warehouse is connected to one or several final consignees. Each of these warehouses is rented by the LSPs. The selection of warehouses is made by the LSP and according to its adopted strategy. It is called the "selection strategy". We provide four different strategies. The first one is a reference strategy: warehouses are just selected randomly. The

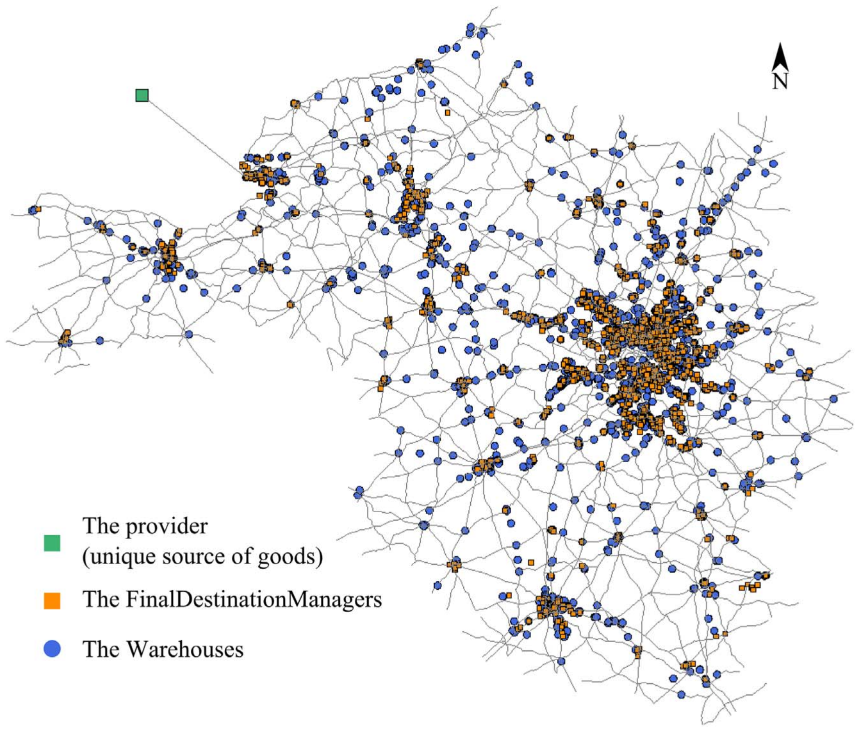


Fig. 8. The road network and the position of agents on the GAMA Platform during a simulation.

second one chooses the largest at the warehouse national level, and the closest ones to the final consignee at local level. The third one is similar to the second one since warehouses are selected randomly but with a bias as to surface (national level) or distance (local level). And the fourth one integrates another bias about the accessibility of warehouses (in terms of Shimbel (1953)'s accessibility).

Once a day, LSPs control the stock levels of all the warehouses they manage. This is called the "restock strategy". If the quantity of goods of a specific stock is under a minimal threshold, then a LSP orders a replenishment of this stock to the warehouse (or to the final consignee) from the higher level in the supplying network. Each LSP may have a different value of the minimal threshold. The restock strategy allows to well-balance the stocks in the infrastructures of the supplying network and to facilitate the atomization process of the flow of goods.

Fig 8 represents these infrastructures and agents during a simulation. At each step of a simulation (one step equals one hour), each agent can make reactive decisions according to their needs and to the environment. These decisions generate the movement of goods on the network and modify the flows. We notice that there are only relationships with the agents inside the modeled system. Therefore the flow of goods generated by these relations only occurs through the territory of our system. Only the goods provider agent connects the territory with its external environment.

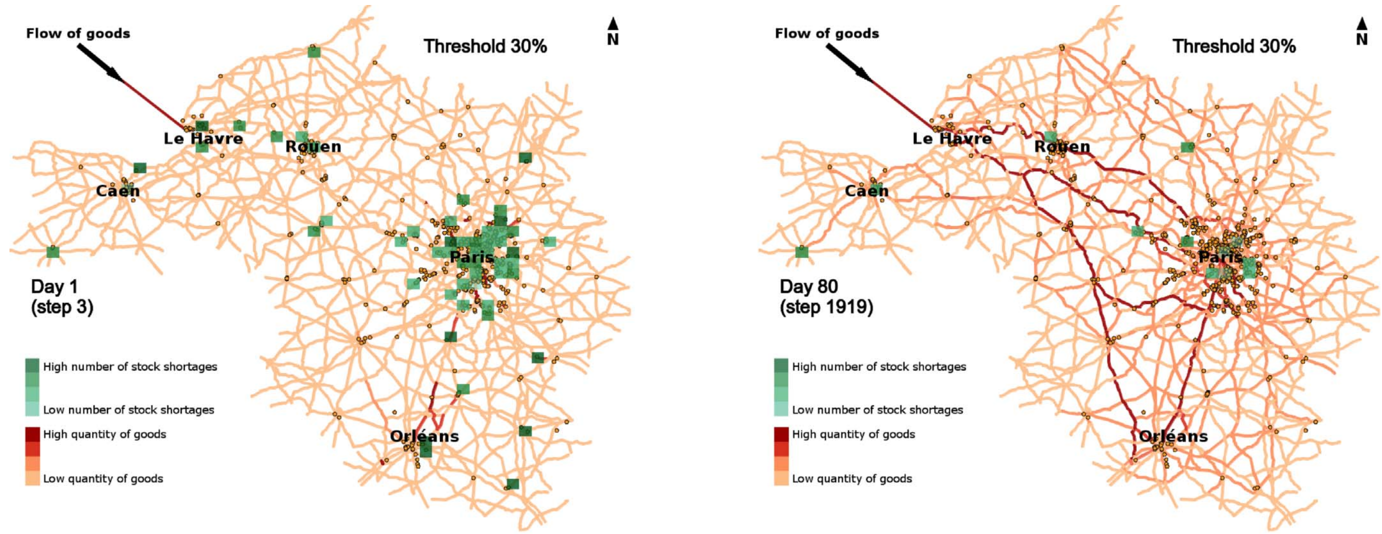
During a simulation, the moving goods are represented by an agent called Vehicle. One Vehicle agent carries at the same time and at the same date all the goods that are managed by the same LSP, and whose source-destination is the same. It moves along the network according to the speed attributed to its edges like a classic vehicle (therefore it can take more than one step to go from one source to its destination). However, a Vehicle can transport more goods at the same time than a single vehicle: it is an aggregation of vehicles. It represents vehicles at a higher level. It limits CPU load by limiting the number of agents. This agent leaves a trace on the edges as it passes. It corresponds to the quantity of goods it carries (it is used to color the edges). As the pheromone used in ant colony optimization algorithms (Colorni et al., 1992; Dorigo, 1992), these traces "evaporate" progressively. It means that, at each step, a coefficient makes the trace decrease on every edge. Since the traffic is dynamic, if the agents stop using an edge which was particularly congested, the trace on this edge will decrease. It highlights the evolution (the dynamics) of traffic.

The modularity of the simulation with the initial data and parameters is particularly interesting to help the decision process of land planning because the effects of a specific decision can be quickly highlighted before it is taken into the real world. We could compare simulations with different initial scenarios: what happens if we have a new highway? What happens if some warehouses are destroyed, and/or new ones are created?

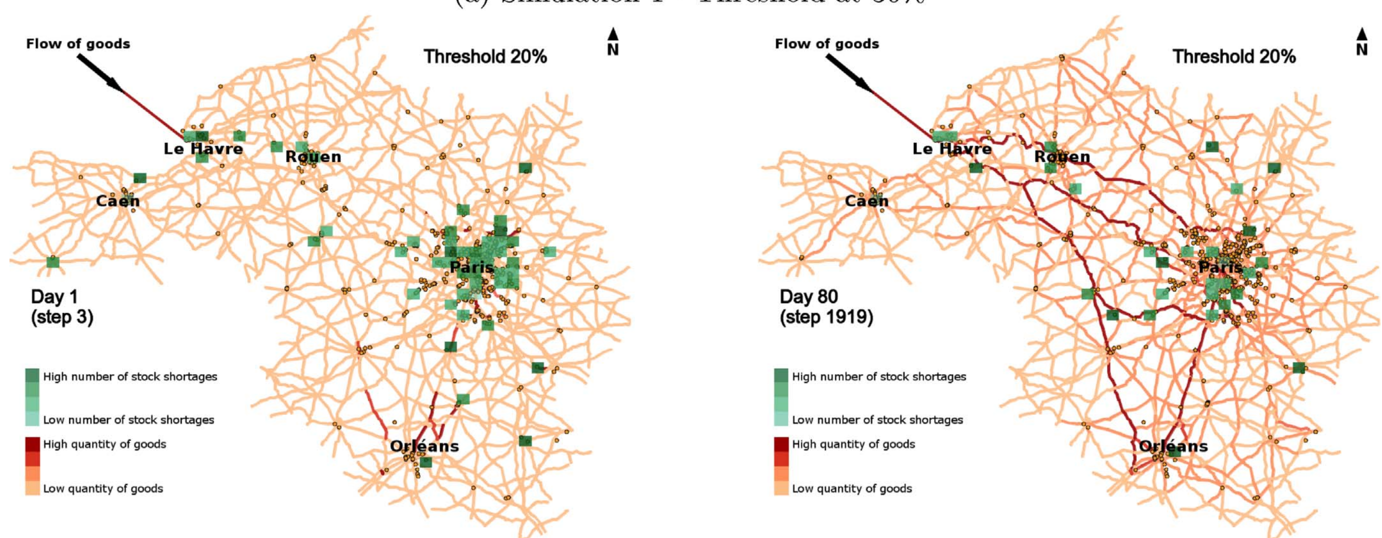
4.3. Results and discussion

The results will, on the one hand, allow us to check whether the model is realistic, and on the other hand, help to understand particular aspects of the model. For instance, dynamic and static graphs can be generated in order to observe spatial clustering of infrastructures thanks to neighborhood graphs. The whole set of measures gives the opportunity to see the impacts of particular parameters on the output of the simulation.

Fig. 9 shows the evolution of two simulations with two different configurations. The figures show the system state of both simulations on the first day on (step 3, just after initialization) and on the 80th day (1919th step, when the simulation is stabilized). At initialization, we observe that the two simulations look similar: they both start with comparable initial amounts of goods inside warehouses. But after stabilization, we notice differences. Their respective evolution diverges due to the different restock strategies used by LSPs. Indeed, this figure shows the effects of a parameter on the stock shortages: the threshold at which a LSP orders the transportation of goods because stocks in a place are too low. For instance, with a threshold of 30%, the LSP orders the transportation from a higher level warehouse in the supplying network only when the stock quantity goes under 30% of its maximum capacity. On the output, the environment is divided into 50×50 cells which take a coloration according to the number of unavailable products: at each step, each cell computes locally the percentage of stock shortages compared to the local total number of stocks. The more dark green they



(a) Simulation 1 - Threshold at 30%



(b) Simulation 2 - Threshold at 20%

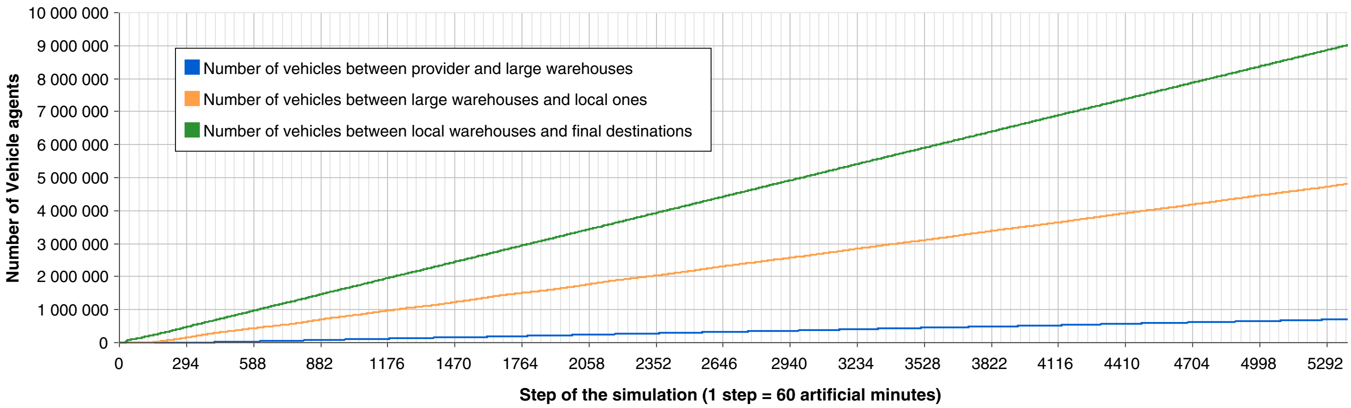
Fig. 9. Two simulations executed with two different initial configurations of restock strategies.

are, the more there are stock shortages within the square. The orange dots are the position of each final consignee. The efficiency measure used by the final consignees is the average number of stock shortages. For the purpose of this study, we force every LSP of the same simulation to adopt the same threshold value as replenishment strategy.

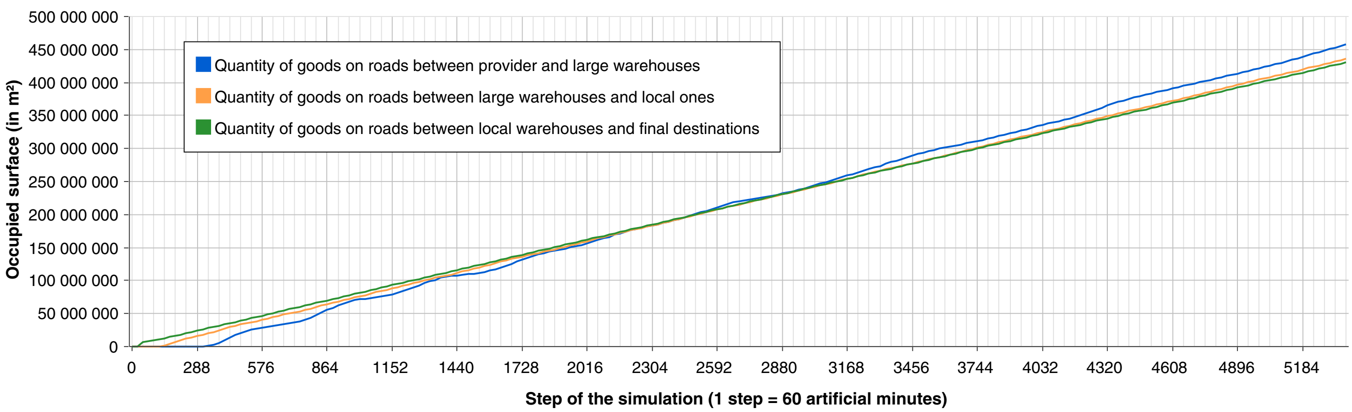
At the beginning, the two simulations have many stock shortages all over the territory. On the 80th day (1919th step), the simulation with a 20% threshold has more unavailable products than the simulation with a 30% threshold. The two simulations highlight that when the threshold is lower, the LSPs have less time to replenish. It does not give them enough flexibility. So the products are less available. A high threshold corresponds to a more efficient way (in terms of stock shortages) for the LSPs to manage the stocks. Yet a high threshold will increase the frequency of goods delivery, as well as the costs of transportation. The simulation can help to find the best threshold to minimize the number of stock shortages but also the costs of transportation.

Secondly, Fig. 9 also shows where traffic is concentrated. We observed the appearance of corridors on the Seine axis connecting Le Havre, Paris, Rouen and Orleans (the main urban areas). As observed in reality, traffic follows the main roads, such as highways, connecting these main urban areas. However, we do not observe flow going North of the Le Havre-Paris axis: indeed, the modeled territory does not include a major city in the North of this system, otherwise there would be some flow going to this direction. It highlights one of the limits of the model since it is closed: there is no relationship with actors outside the territory (except the goods provider). It might be a perspective to create new connections with the outside.

Fig 10a shows the evolution of the cumulative number of Vehicle agents which are moving on the road network. These agents are sorted into three subsets according to the level, in the supplying network, of their destination. We can see that there is a hierarchy between the different curves. Indeed, they do not expand at the same speed. The curve corresponding to the Vehicle agents going to the final destination increases faster than the curve corresponding to the Vehicle agents coming from the goods provider. It means that the closer in the supply chain to the final destination we are, the more Vehicle agents there are. This is due to the way the supplying networks are built: one goods provider, a small number of national-level warehouses, and numerous local-level warehouses. Next, if we now consider, the quantity of goods within these Vehicle agents sorted in the same way (see Fig. 10b), we do not observe the same hierarchy. Indeed, the three curves have more or less the same gradient. It means that the quantity of goods, by kind of



(a) The cumulative number of Vehicles moving on the roads.



(b) The cumulative amount of goods within Vehicle agents moving on the roads.

Fig. 10. The evolution of the number of Vehicle agents and their amount of goods.

Vehicle agents, is the same at each step. Thus, if we make a correlation with the results of Fig. 10a, we recognize the same principle of atomization of flows that we observe in reality.

The simulation describes realistic characteristics according to the flows of goods over the territory. This is due to the agents/actors system and the spatial constraints of the simulation. Yet we do not integrate all the complexity of reality. The model must be limited by concentrating itself on the main aspects of this system in order to facilitate its understanding. However, the agent paradigm is known to provide evolving models. It is still possible to integrate more complex behaviors or other parts such as multi-modality in the future.

5. Conclusion

This paper had two main goals: first, to help understand how a logistic system works and how it is structured and organized into a hierarchy; and secondly to provide a model which can help the decision making of land planning. The model presented here brings a view of a logistic system shaped as an interface between the port and urban areas and which works as a buffer zone. The necessary and accurate description of actors and infrastructures of a logistic system in the first section explains how and why the whole logistic system can be seen as a complex system. The three inter-connected kinds of logistics that describe macro-patterns emerged from micro rules. This way of seeing a logistic system leads to modeling this environment thanks to approaches from the complex systems theory. An agent-based model coupled with dynamic graphs has been chosen to design the model. Our approach to model a logistic system integrates spatial properties of actors and infrastructures on the contrary of other often-used approaches such as dynamical systems. Moreover, the algorithms from the graph theory give the opportunity to analyze some results.

The implementation of the model helps to give answers about the organization of the logistic system. The simulation is adapted to the Seine axis but it is compatible with other systems if the user takes time to fit the agents' behaviors to the specificities of the chosen system. In this paper, the implemented simulation is focused on the movement of goods over the territory through a supplying network. Therefore, it works on a subset of the actors and infrastructures described before. The results show that the simulation has realistic aspects such as the choice of roads preferred by agents, or the atomization phenomenon from the port logistics to the urban one, thanks to the interface. Moreover, the different methods of analysis developed pinpoint the impacts of some parameters on the system, such as the replenishment strategies. The input data can be set and the simulation could show, for instance, the effect of a large logistic platform located at a very accessible place. Furthermore even if data about the Seine axis are used, the implementation is generalist, therefore the model can simulate another logistic system. So the implementation provides features of decision support.

In the future, we want to observe the effects of the strategies adopted by the LSP agents to build and manage the supplying network. A first step in this direction has been made in Démare (2016), Démare et al. (2016). It would be useful in order to compare the system's logistic performances according to these strategies. For the moment, the system has only one entry through the port of Le Havre. In the next step we would like to offer the agents the possibility to select another port, such as Antwerp. It would help to study the competition between the two ports, and observe how the corridor organizes itself. We also want to integrate a community detection system in order to highlight groups of actors who work together in an efficient way. Eventually, we want to integrate multi-modality into the simulation in order to study the advantages entailed by one mode rather than another, and observe the evolution of the different mode uses. These future features will improve the capacity to help the decision making of spatial planning.

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