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

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ABSTRACT

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*