Freight transportation systems: a taxonomy

Freight transportation systems: a taxonomy

Teodor Crainic[1,2], Guido Perboli[2,3], Francesca Perfetti[3]

[1] Ecole des sciences de la gestion, UQAM, C.P. 8888, succ. Centre-ville, Montreal (Quebec) Canada
[2] CIRRELT, Pavillon André-Aisenstadt, CP 6128, Succursale Centre-ville, QC H3C 3J7, Montréal, Canada
teodorgabriel.crainic@cirrelt.net
[3] Politecnico di Torino, corso Duca degli Abruzzi 24, Torino 10129, Italy
{guido.perboli, francesca.perfetti}@polito.it

Keywords: *Freight transportation, Intermodal systems, Taxonomy, Simulation, Simulation-Optimization*

1 Introduction

In the past decades, several phenomena like globalization, urbanization, the proliferation of online shopping and technology innovation have led to the development of geographically extended and complex supply chains as well as an increasing freight transportation activities within urban areas. Today, supply chains are composed of several actors (shippers, carriers, customers, infrastructures managers and institutional authorities), each one having its objectives and taking its own decisions. Shippers generally have the role of senders of the goods and they organize and plan shipments in order to satisfy their customer, while carriers are those who physically realize the transport for the shipper. Customers are the receivers of the shipment and they can be the final client, the retailer, the distributor or the wholesaler. Furthermore, customers are also residents, so they select whether they should make a complaint to administrators or not. Infrastructures managers can be both public entities or private firms and they usually are separated entities from who plan, organize and realize freight transportation services. They apply pricing policies to carriers and they can establish partnerships with carrier companies. Finally, institutional authorities (e.g. government and public administrations) are the actors who tax, incentive and regulate transport activities as well as they offer transport infrastructures. The interconnectedness of these different actors in the supply chain has rendered such a system as a large complex system which is difficult to describe, forecast and manage. Furthermore, the more complex supply chains usually involve different transportation modes (air, inland, water, ocean, pipeline, rail, and road). New simulation models have been developed in order to reproduce the dynamics of a supply chain and to support decisions making process. Particularly, while simulation and optimization were traditionally considered separate approaches, the development of computational power allowed the diffusion of methods that combines them. These methods allow to better consider uncertainties, nonlinear relationships and processes hardly modeled by analytical expressions. Nevertheless, while the number of simulation models applied to logistics and supply chain issues is growing, at the best of our knowledge, a taxonomy able to classify simulation approaches applied to intermodal freight transportation systems and supply chains does not exist yet.

In this paper, we present a taxonomy of freight intermodal simulation systems. The purpose of this work is threefold: first, we aim at providing a practical tool to compare two or several

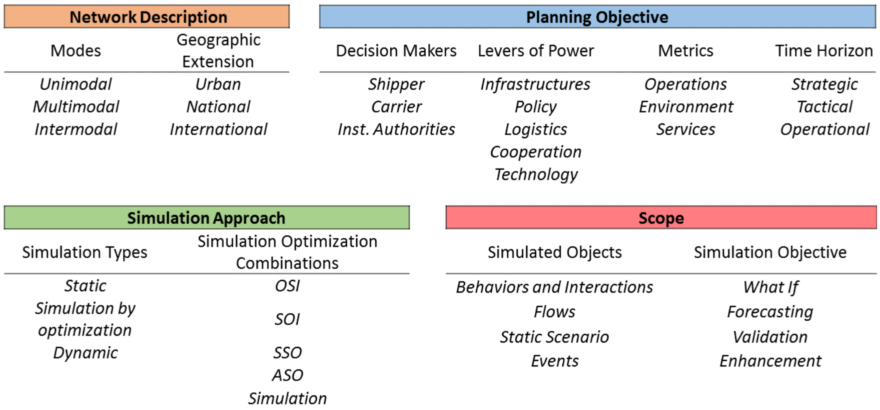

Figure 1: Taxonomy structure

models, to extract and analyze new trends and to guide researches analysis. Second, simulation of intermodal freight transportation systems are relatively a recent topic in literature, particularly the optimization - simulation models, but there is not a classification able to give an overview of the different approaches. Hence, this taxonomy aims at identifying and defining the relation between simulation and optimization, and at giving an overview of the full spectrum of current simulation applications in this field. Third, we apply our taxonomy to a set of 75 papers and we conduct a statistical analysis in order to highlight new trends and gaps. Thanks to the taxonomy, we develop a systemic and complete overview of these issues.

2 The taxonomy

The first step for constructing the taxonomy was the identification of major characterizing factors and the extraction and analysis of trends. We retrieved papers from the literature, using scientific refereed journals and refereed conference proceedings as a source for intermodal freight simulation literatures. Figure 1 presents the structure of our taxonomy. The taxonomy is composed of four main axes: *Network Description*, *Planning Objective*, *Solution Approach* and *Scope*. The first two axes concern problem specifications, while the third one informs on how simulation approaches have been implemented and the fourth axis investigates the role of Simulation. Each axis is structured at the second level through a number of categories, for which more precise information is given at the third level by their subcategories.

Network Description identifies the network involved through two categories: *Modes* and *Geographic Extension*. *Modes* considers the modes which the network is composed of. Transportation modes are road, rail, inland navigation, maritime transportation and air. We identify three main types of network in relation to the modes involved in it: unimodal, multimodal and intermodal network. Unimodal networks consider one unique mode for freight transportation, while multimodal ones involve a modal shift along the supply chain. Besides, intermodal freight transportation refers to a multi-modal chain of container-transportation services where, further on the multiple modes transportation management, additional services in terms of freight treatment are considered. *Geographic Extension* refers to the geographical dimension of the supply chain, classified in international network; national network, which involves movements within a country as well as interurban networks; and urban distribution, which deals with transportation issues in urban areas, characterized by traffic and congestion problems.

The second axis is named *Planning Objective*. This axis aims at defining who is taking the decision and which type of decision is investigated. Each model supports an actor in his decision making process. The category called *Decision Makers* specifies which actor is taking the decision, which determines the point of view of the problem. The actors considered are: shipper, carrier and institutional authorities. However, intermediaries such as 3PL can perform several activities which cannot be addressed to one specific actor because of their hybrid role within the supply chain. Hence, we classify them according to the task analyzed in each paper, which usually focus on one or a set of activities as shipper or carrier. Once the decision maker is identified, the taxonomy defines the problem that has to be solved. *Levers of Power* denotes the type of problem that has been studied in each paper. We grouped problems within 5 subcategories: Infrastructure, Policy, Cooperation, Technology, and Logistics. *Metrics* represents the target of the problem. In particular, it informs about the goal of the objective function and about the metrics used to measure and compare the effectiveness of alternatives: operations, environment and service. *Time horizon* expresses the time perspective of the problem. Planning activities can be divided into three different levels: strategic, tactical and operational. Thus, *Time horizon* is composed of three subcategories: *Strategic Planning*, which consists of long term planning decisions which require the highest level of forecasting, investments and management; *Tactical Planning*, which deals with medium term horizon; and *Operational Planning*, which concerns short time horizon and we also included in this subcategory the decisions taken in real time. These categories are complementary to determine objectives, formulations and requirements of the problem.

Once an overview of problems has been described, we investigate which approaches papers propose. The *Solution Approach* axis is composed of two categories: *Simulation types* and *Simulation Optimization relation. Simulation types* groups simulation approach into three subcategories: *Static simulation*, *Simulation by Optimization* and *Dynamic simulation.* To describe the combination between simulation and optimization, we applied the following classification:

- *Optimization with Simulation-based Iterations (OSI)*: during an optimization procedure, one or multiple complete simulation runs are performed;
- *Simulation with Optimization-based Iterations (SOI)*: during an simulation process, one or multiple optimization procedure are performed;
- *Alternate Simulation-Optimization (ASO)*: both modules run alternately and in each iteration, either both run completely or both run incompletely with feedback loops;
- *Sequential Simulation-Optimization (SSO)*: both modules run sequentially (either optimization following simulation or the opposite);

To these four possible combinations, we added the case where only Simulation is implemented:

- *Simulation (SIM)*: Simulation, without Optimization procedure

The last axis of the taxonomy is *Scope*, which investigates about the role of simulation. It includes two categories: *Simulated Object* and *Simulation objective. Simulated Object* identifies what is simulated. We consider that simulation can be applied to simulate: stochastic *events*, realistic *static scenarios* (here a simulation framework is created to set up the scenario to which the optimization procedure is then applied), *behaviors and relationships* of several entities' which interact each other, and *flows*. Finally, we propose another perspective of analysis looking at the purpose of simulation models. We identified four main roles of simulation tools. Simulation can be implemented for: *What If analysis* (or"What If simulation"), which consists of the analysis hypothetical systems and compare two or more systems; *Forecasting*, Simulation allows to study and evaluate the characteristics of real system in the future as well as to predict its performance in the future; *Validation*, Simulation allows to validate a proposed solution, a mathematical model, a modeling approach or a new policy; and *Enhancement*, Simulation is combined with Optimization in order to test the solution proposed by the optimization model and to suggest how to improve the solution. This usually requires an alternate Simulation and Optimization procedures, connected through performance feedback loop.

3 General trends and research directions

In the following, we give some highlights of our findings after applying the taxonomy to a set of 75 papers. First of all, the analysis includes a large set of papers, published in a multitude of scientific reviews. This is a confirmation of the multidisciplinary of Operations Research applications in freight transportation, involving Computer Science, Mathematics, Transportation Engineering, Management Science and Economics. However, a concentration of papers is published in Procedia - Social and Behavioral Sciences. Some of the most important international and European conferences on transportation (City Logistics Conference and EWGT) are published in this journal, making Procedia - Social and Behavioral Sciences the reference journal for OR applications to freight transportation. Another important result of the analysis is the focus of studies on intermodal networks, even if the majority of papers is focused on a specific part of the supply chain, in which just one mode is involved. Particularly, the most recent papers consider unimodal networks. This is due to the increasing attention on urban areas, where the main mode used is road transportation. In fact, all papers proposing new policy and solution for freight distribution within cities consider just trucks or trucks and electric vans. Hence, intermodality arises to be very successful for interurban, national and international networks, while in urban areas, it seems that freight distribution is realized mainly by unimodal road transportation. In addition, since 2007, the attention of researchers to urban context have been increasing as well as the attention to the environment. Environmental aspects arise to be basically considered in urban areas. However, they are generally taken into account by means of generalized costs or indirectly, e.g. measuring traffic reduction, road occupancy, travelled kms or in CO2 equivalent units. Only few papers directly estimate the GHG emissions measuring CO2 or NOx emissions in tons. Furthermore, there are very few examples of papers proposing a multi criteria approach, able to consider at the same time different metrics for the comparison of potential alternatives. Because of the multi criteria nature of the urban supply chain, it would be interesting to integrate Simulation and the multi criteria analysis. Looking at the decision makers, an interesting result is the role of Institutional Authorities. They arise to be very active and interested in the improvement of freight distribution within urban area, particularly by reducing the environmental impact. This is may be the consequence of the direct involvement of the public sector in City Logistics projects. This would also explain the fact that their studies insist on an operational perspective, while it lacks an evaluation of policy impacts on the whole system in the long time horizon, as well as a qualitative insight into the possible reactions of the system to a new policy or a new decision. Moreover, there is not a significant presence of public authorities as decision makers in national contexts. From a modeling point of view, *Dynamic simulation* is the most applied. This type of simulation is particularly used to reproduce both the behavior of several entities and the dynamism and interaction between them. There is an increasing number of studies proposing multi-agent simulations, in which optimization models are applied to reproduce the behavior of agents. In addition, we found several examples of network optimization models within *Simulation by Optimization*. While traditionally these models enable the prediction of multi-commodity flows over a multimodal network that represents the transportation facilities at a level of detail appropriate for a nation or region, more recently they focus more on predicting urban goods movements, simulating freight tours within urban and metropolitan areas and combining urban passenger and commodity flows.