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Directions for research

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Invited Research Paper

Predicting the effects of logistics innovations on freight systems: Directions for research

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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

Logistics processes underlying freight transport are changing rapidly, driven by progress in information technology and an unparalleled growth of consumer involvement in supply chains. This development is also driving change in freight transport flows, by all modes of transport. We argue that an understanding of logistics innovations is a prerequisite for effective explorations of future freight flows and design of transport policies. Our main objective is to review these innovations and derive needs for research into freight modelling. We focus on 3 basic dimensions of model improvement: the structural elements of the system that are modelled, the functional relations between these elements, and the dynamic properties of models.

1. Introduction

Although freight represents a minority of the flows on our transport networks, it can be of decisive importance for infrastructure costs, traffic performance or negative external effects of traffic. The direct and indirect economic impact of freight transport accessibility is considerable, and increases further with the ongoing globalization of the economy. Ways in which this is becoming visible is the stronger growth of freight transport than passenger flows, the multitude of service possibilities offered by firms and the increasing diversity of scales of transport processes, from single parcels to megaships. After recent supply chain disruptions created by natural disasters, the risk of a lack of supply of goods has also become a tangible factor. Life without trucks due to access disruptions has become a familiar threat for cities. The importance for consumers of e-commerce, individual shipments and instant deliveries can hardly be underestimated. As a result, in recent decades, freight transport has continuously been growing in significance for transport policy makers. This growing pervasiveness has presented new questions relating to e.g. infrastructure spending, transport pricing, service market regulation and decarbonization.

Our main objective in this paper is to review contemporary changes in logistics innovations and derive requirements for freight modelling. The main purpose of freight modelling is to supply quantitative evidence for policy making and, towards the industry, for logistics innovations. We argue that, to remain up to date, freight models should move along with all major policy ideas and innovations.

We build on the recent short communication on the future of freight modelling by Meersman and Van de Voorde (2019) by a focused discussion about logistics innovations. As in the above paper, our focus here is on the descriptive and predictive transport models, that feed into ex-ante evaluations of transport policies and innovation programs for freight transport systems. We do not address ex-post evaluation of policies or models with a solely prescriptive purpose (i.e. optimization and control-centered models).

In the next section, we first explore the main directions of innovations in logistics systems. Subsequently, in Section 3, we discuss how these concerns can give direction to new approaches for quantitative modelling. We conclude with recommendations for policy and research in Section 4.

2. Innovations in logistics and transport policy

Technological innovations like digitalization and automation are transforming the logistics industry. Supply chains are responding to new opportunities to provide digital services with new business models, and logistics and transport processes are reorganized as part of these changes. Service propositions related to physical products are being developed into product-service systems (Tukker, 2004). Innovative services support the on-demand economy through, for example, crowed-sourced shipping models (Dablanc et al., 2017). The question in the seminal paper of Fisher (2003) – "What is the right supply chain for your product?" is now answered in more ways than ever, as nowadays all channel possibilities are offered simultaneously in omnichannel distribution approaches (Ishfaq et al., 2016). This improved customer

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focus involves high investments and has led to a subsequent pressure on the industry to rationalize. Coordinated by supply chain control towers, flows are bundled wherever possible to capture potential scale economies, creating large scale flows at slow speeds in the back-offices of distribution channels, well before the order decoupling points to customers. This variation of scales within a supply chain is unprecedented, and is predicted to continue in logistics systems for decades ahead – supported by increased modularization of loading units and collaboration between shippers and service providers, in transport and warehousing (Montreuil, 2011). These innovations in logistics are expected to have a profound economic impact. The World Economic Forum estimated that the social value of innovations would add up to several trillions USD in 2025 (WEF, 2016). Fig. 1 indicates the contributions of different types of innovations.

The following salient points emerge when looking at the analysis:

- The largest economic impacts are expected from an improved utilization of assets through collaboration, and an increasingly automated control of logistics operations.
- Valued by current market prices for external effects, the external cost reduction from logistics innovations is minor. Negative effects are even expected from some innovations.
- There is little clarity about distributive effects, i.e. which stakeholders or sectors will benefit.

Because of their expected impacts on sustainability in all its dimensions, these changes present new challenges for policy makers. The performance of the transport system will be affected in different, often contradictory ways, due to trade-offs inherent in these innovations. Efficiency improvements may go at the cost of resilience, or environmental and social sustainability (ITF, 2018). In order to quantitatively understand the behavior of markets and the impacts of policy, improved models are needed of these systems that are able to capture the new mechanisms of logistics processes in numbers, and predict possible outcomes. Before discussing modelling, we briefly turn to the relationship between logistics innovations and transport policy.

In contrast to innovations in passenger transport organization and technology, we are not aware of any literature that systematically explores the new policy questions that logistics innovations lead to. Typical general questions in freight transport policy relate to the societal impacts of freight transport, measures to support the sector and measures to mitigate negative impacts (Savy and Burnham, 2013). As all dimensions of sustainability are affected, questions about impacts are as broad as for passenger transport. Efficiency aspects need to be assessed by formulating new business models or even business ecosystems, using multi-actor, multi-function and multi-decision frameworks. In order to address environmental concerns, supply chain optimization needs to be reviewed and revised for its sustainability, or greening impact. Social equity effects of innovations require us to understand welfare distributing impacts of technology on diverse user and non-user groups. Table 1 lists some typical policy questions related to logistics innovations. We distinguish between 5 groups of innovations: mass-individualized logistics services, freight network integration, globalization dynamics, digitalization and advanced transport technologies (see Tavasszy, 2018a for an elaborated description).

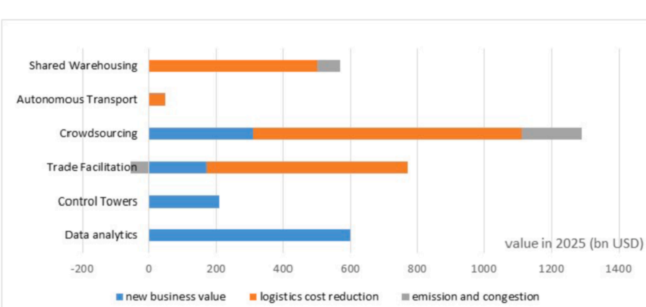

Fig. 1. Expected value of innovations in logistics (data: WEF, 2016).

Table 1
Typical policy questions by category of innovation.

Innovation	Policy question
Mass-individualized logistics services	• Which agents will develop these services (Current forwarders, carriers, independent platforms?) and with which business models? • What will be the net impact on transport and traffic, taking into account displacement of shopping trips and consolidation? • How to best support businesses (e.g. 3D printing) with new technologies and their servitization?
Globalization dynamics	• Impact on global shifting of manufacturing activities, trade patterns and trade routes? • Impact on creation of new pollution havens? • Geographical imbalances in working conditions?
Network integration and synchronization	• What are promising policies that could enhance collaboration in the fragmented logistics sector, to allow better utilization of assets? • How will this affect the use of high capacity modes and vehicles? • What level of efficiency improvement can be achieved by coordination and joint optimization of freight operations, beyond investments and planning? • What are the possible negative impacts on resilience of an improvement in efficiency?
Digitalization	• Which technologies will become adopted when, in the logistics and transport sector? • How to support freight system digitalization to optimize effect on the economy? • How to deal with digital divide between generations, or large firms and SMEs? • What is the expected impact on the environment?
Vehicle technology (autonomy, propulsion)	• What are promising new transport technologies and what is their expected market? • How can the use of these technologies be stimulated or regulated? • How do these technologies fit in roadmaps for energy and environmental transition • What is the impact on transport system equity and resilience?

In summary, we see many technological challenges in the development of freight and logistics systems, accompanied by changes in policy and innovation processes, which also have a wider societal dimension to satisfy sustainability constraints. We define the necessary innovations in freight modelling along these lines in the following.

3. Directions for freight modelling research

The new policy questions arising will require advances in quantitative modelling, both in terms of methods as in terms of empirical applications. We discuss these changes in 3 general directions of advancement in modelling: (1) the structural properties of models, i.e. the innovations as objects of interest within and around the freight system, (2) the functional properties of models, describing the relationships between innovations and aspects like their use and impacts, through physical models and decision making behavior and (3) the dynamic properties of models, tackling the aspect of time.

1. The constituent elements of new freight and logistics systems can be identified from comprehensive visions by practitioners (e.g. WEF, 2016; ALICE, 2017) and academics, e.g. on the Physical Internet (Montreuil, 2011) and on cyber-physical systems (Zezulka et al., 2016). Models should also address relations with the neighboring energy, climate, finance and ICT systems.
2. Prediction of the impacts of innovations relies on understanding of the relevant behavioral mechanisms. Freight models are becoming

more and more refined in terms of their predictive ability of behavioral responses of firms. Besides including the main logistics decisions, the roles and relations of stakeholders should be recognized.
3. The need to understand the dynamics of freight systems has grown in importance. Policies need to be adapted to time-definite policy objectives like decarbonization. In cases of disturbance of the freight system, time to respond is critical for resilience. Also, innovations and policies have become cyclical and adaptive processes, requiring more advanced predictive capabilities.

These innovation directions are interdependent and will reinforce each other at various levels, including modelling research, software development and policy applications. Arguing that all 3 dimensions need to be addressed to support logistics innovation, we discuss them in more detail in the subsections below.

3.1. Structural elements of freight transport systems

The different innovations in logistics introduce many new elements into the freight transport system which are currently only represented to a very limited extent in freight transport models. Table 2 outlines these elements – we discuss them below.

Mass-individualized logistics services require a re-definition of current conception of demand and supply of goods in freight models. Shipments can move via different distribution channels, dependent on the consumer's wishes. Most current models do not consider distribution channels at all, apart from indirect delivery through national or regional distribution centers. Exceptions are (Friedrich, 2014; Davydenko et al., 2013 and Sakai et al., 2018). The gradual replacing of shop sales by e-commerce creates a potential reduction of shopping trips. Understanding the consequences of these for shopping behavior and the associated personal transport movements is also a relatively new field of research.

Many innovations have a global reach and require also models of the global freight transport system. Although global trade models are widely available, these do not explain changes in spatial patterns of manufacturing or transport. Recently, new models have become available for global transport flows (see Halim et al., 2019 for an overview). These have several shortcomings, however, including limited integration with spatial economic models.

Network integration and synchronization innovations have created a wealth of models focusing on multi-modal, intermodal and synchromodal networks (SteadieSeifi et al., 2014). Most of these however relate to the design (i.e. optimization) challenges of networks and not to the prediction of likely outcomes in terms of flows, efficiency and final impacts, on the broader transportation system. Many models also include flow models, but these often are assume deterministic carrier behavior concerning mode and route choice (Zhang and Pel, 2016).

Table 2
New transport system elements.

Innovation	New elements
Mass-individualized logistics services	• Increased diversity of logistic services: supply, demand, markets • Distribution channels • Crowd-sourcing of services
Globalization dynamics	• Global transport flows, networks and impacts • Production locations: offshoring, nearshoring of flows
Network integration and synchronization	• Tactical and operational network planning • Collaborative networks (control towers, joint sourcing and planning of flows) and its economics
Digitalization of information and communication	• Information and data availability and flows • Shared situational awareness • Information networks
Transport technologies (autonomy, propulsion)	• New modes and their attributes • Role & impact of transport means in SC • Energy systems

Technological innovations in freight transport systems relating to digitalization, add a new dimension to freight transport models: information availability. Most models that describe decision making processes make the (implicit) assumption of availability of information. Information as part of transport services, absence of information in supply chains, different levels of information, economic valuation of information and information asymmetry are not included in descriptive models, and their impact on decisions is unknown. This restricts our ability to forecast the effects of increasing availability of information.

An important challenge is to be able to describe convergence of transport technologies. For example, the charging of electric drivetrains requires a change in the design of electricity grids. Where there are larger power requirements (e.g. peaks in charging demand, high-capacity batteries or frequent opportunity charging in cities), the existing energy infrastructure may constrain logistics operations. Adoption of electric vehicles will therefore depend on availability of energy infrastructure, which will have to be modelled separately.

Eventually, freight transport models need to be detailed to connect to environmental (energy, emissions, health) models, economic models of the manufacturing and services sector and business process models of the financial sector. These models will also allow to study trade-offs in integrative systems of which the freight transport system is a part, including:

- performance of the freight transport system vs performance of the broader system (e.g. additional freight activity needed to create a sustainable energy infrastructure, cf. McKinnon, 2018)
- Conflicts between performance dimensions, e.g. efficiency, resilience and environmental performance (see e.g. ITF, 2018).
- Different stakeholder groups affected by transport policies, or distributive effects (see e.g. Ballantyne et al., 2013).

3.2. Functional properties of models

In order to assess the impacts of innovations and policies, the ability of models to predict logistics "reorganization effects" (FHWA, 2001) is key. These reorganization effects can involve entire supply chains. While the earliest aggregate modelling approaches of the 1970's were shown to be empirically valid to predict freight flows at a macro level (i.e. regional or national totals), they had little relation with the underlying logistics decision making in firms. Throughout the decades, and especially since the advent of choice modelling in the '80s, there has been increasing attention to detailing out logistics decision making. The vast majority of the literature in behavioral freight modelling has focused on one decision that companies make: mode choice. Other decisions that are addressed in models, but usually without explicit reference to decisions, include production, consumption and trade. More recent work has started to address other choices including supplier choice, outsourcing, distribution centers, shipment size choice, vehicle type choice and routing of flows. Recent frameworks that show how the above choices are related can be found amongst others in (Liedtke, 2009) and (Roorda et al., 2010). Here, longer term trade implications, as well as impacts on production and consumption, are explained from within the individual firm's decision making perspective. Note that the field of economic geography already offers models for international trade that are rooted in microeconomic theory (see e.g. Fujita et al., 1999); research that link this framework to logistics systems is rare, however (see McCann, 2013 for an example). A comprehensive framework for studying logistics re-organization effects that includes all relevant logistics decisions is still lacking. Logistics management involves close to 50 interrelated decisions (see e.g. Riopel et al., 2005) that, directly or indirectly, drive freight transport. Recent work maps the existing choice models against logistics decision making frameworks

(Tavasszy et al., 2019). Fig. 2 summarizes these decisions in 3 different categories of logistics management.

The state of the art in this area is moving towards forms of multi-agent modelling, in which behavior can be described in more detail. Opportunities should be assessed on their potential to improve transport predictions or to enhance policy making. New research directions feeding behavioral models include Agent Based Modelling, with explicit treatment of stakeholders (Anand, 2015; Le Pira et al., 2017) based on principles of agency (Hensher and Figliozzi, 2007), gaming (Kourounioti and Tavasszy, 2017) and game theory based models (Holguín-Veras et al., 2011). The use of such advanced models in practice is still limited, however.

In addition to the modelling problem of reproducing outcomes of individual decisions, reproducing decision processes within and between firms are a separate, unmapped dimension. In order to extend descriptive models with dynamics and interdependence of decisions, work is needed in management research that explains who takes decisions about which aspects of logistics and when (i.e. in what sequence and with which frequency).

Finally, there is more and more attention to resilience of freight systems from the perspective of finance, energy, ICT, security and climate change. Depending on which type and degree of uncertainty is assumed, different modeling approaches are needed. If one wants to consider these uncertainties that are difficult to predict or even imagine (also termed black swans or deep uncertainty), one will need to move beyond traditional scenario-based and simulation based approaches towards forms of exploratory modeling (Walker et al., 2013). Here, the entire space of possible outcomes of combinations of contextual factors will be explored to identify critical combinations of these factors (the "perfect storm scenario"), so that adaptive policies can be designed.

3.3. Dynamic properties of models

It is interesting that there has been so little work on the dynamics of freight transport systems (though, relatively speaking, not much less than in passenger transport) on the dynamics of the system, while the essential role of models to policy and innovations is to provide them with anticipatory capabilities.[1] Assumptions about dynamics are needed to understand the speed of changes in the system, to accurately assess the expected future value of systems, to predict whether objectives with a time horizon can be met and to support the re-alignment of policies and investments with the status quo.

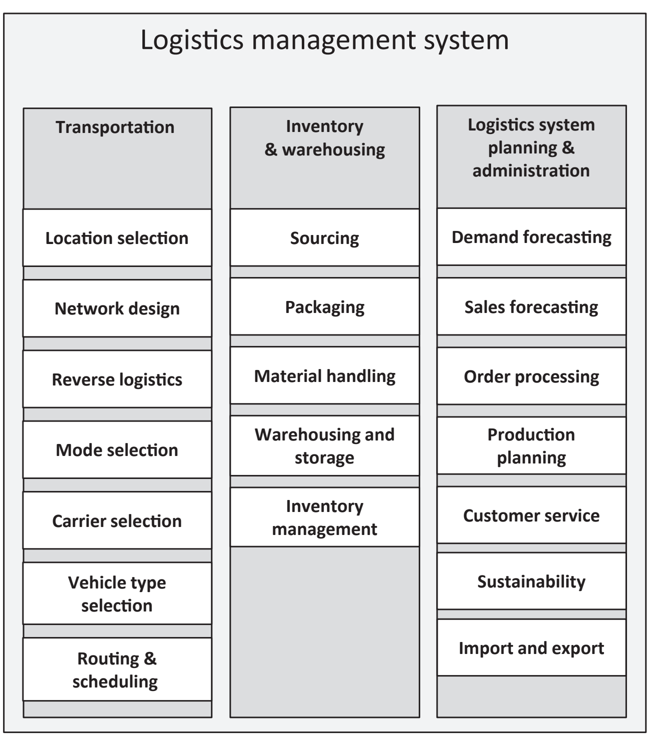

Fig. 2. Framework of decisions from SCM literature (Tavasszy et al., 2019).

Studies about dynamics of larger (i.e. beyond a single company or supply chain) freight transport systems fall broadly into 3 categories. Agent based simulation models have mostly appeared in the domain of city logistics (Le Pira et al., 2017; Marcucci et al., 2017; Anand et al., 2014; Reis, 2018). These predict emerging system level dynamics starting from explicit assumptions about agent level decisions and the frequencies with which these are revisited. System dynamic models seem to be available mostly at national and international level (Balster and Friedrich, 2019; Thaller et al., 2016); they simulate first-order behavior of the system or its parts, using differential equations, without modelling decisions explicitly. Analytical models predict system behavior through system level time series assuming aggregate behavior, or at the underlying agent level using explicit choice models (Tavasszy et al., 1998; Ivanova, 2014; Ferrari, 2014). Typically, in all these models, the typical contextual variables relating to the time factor, like speed of change, inertia, decision frequency, are unobserved and either a result of educated guesses or statistical estimation. Dynamic models of logistics decisions are complex, as each decision has its own dynamic decision context. Such models will need to have a wide span of control to combine decisions at operational, tactical and strategic level.

A second topic concerns the dynamics of implementation and adoption processes involved with freight transport policies. As policy cycles become more aligned with private innovation cycles, freight models are applied to reach shared situational awareness amongst actors about innovations (Kurapati et al., 2012) and to predict mainly short-term effects (see e.g. Nabais et al., 2015). Transport models will be seen and treated more and more as digital twin of the real transport system, providing the real system with short time anticipatory capabilities. This suggests more use data driven AI based analysis, fed by sensors and advanced monitoring systems, and improved predictive capabilities – an automated version of the long term model development and application cycles that are in place today for transport models (Besselink et al., 2016). Fig. 3 illustrates our view on the transport system as a control-loop based management system, positioning several ICT innovations supporting freight transport by different modes.

The figure shows two connected control loops, for example, of different modes of transport that are connected in an intermodal system. The upper box indicating the "brains" in the figure could include a descriptive and predictive freight transport model that provides intelligence for the decision makers. This includes the model of the system that mimics and predicts its movements, as a so-called digital twin. Clearly, dynamics of freight transport processes will need to be understood in much more detail and in operational terms, to be useful for such control-based approaches. The use of this approach for long-term policy making has already been described some time ago by Marchau et al. (2008) as adaptive policy cycles; the approach lends itself also to shorter term cycles, however, down to the level of management of shorter term innovation processes, or even operational freight system management.

4. Conclusions

The aim of this exploratory review was to arrive at a list of challenges for freight transport modelling that are relevant to understand the impacts of logistics innovations. We focus on models with a primarily descriptive and predictive purpose, for use in freight transport policy

[1] An anticipatory system is defined as " … a system containing a predictive model of itself and/or its environment, which allows it to change state at an instant in accord with the model's prediction pertaining to a later instant." (Rosen, 2012).

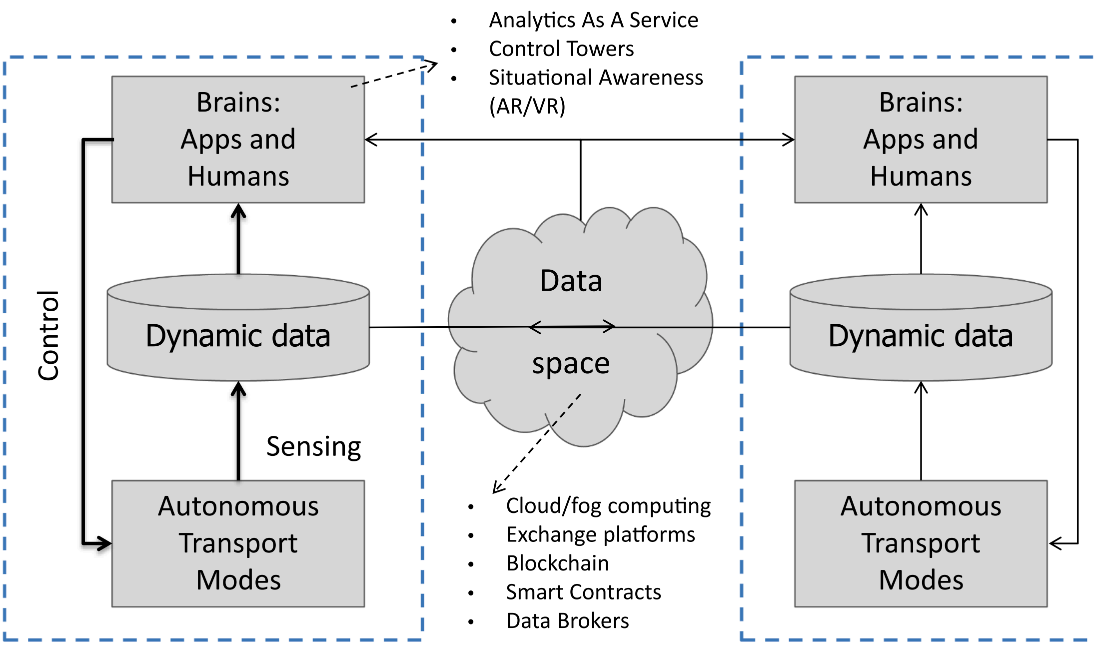

Fig. 3. A control loop based view on the transport system.

analysis. We find that logistics innovations provide important challenges for freight transport policy. On several fronts, the state-of-the-art in modelling can be developed further to tackle today's policy challenges.

We identify modelling challenges in 3 key topic areas:

1. New structural elements of the freight transport system related to innovations, including those in the neighboring systems, like energy, finance, ICT and climate.
2. Improved models of logistics decision making behavior, to predict reorganization responses of firms to policies and innovations, recognizing all relevant stakeholders and their relations.
3. Enhancing the forward looking capabilities of freight models by improved modelling of dynamics, to be able to develop adaptive policies.

We argue that research is needed in all these areas to address contemporary innovations. Programming this research and bringing the research to impact at the policy stage requires a concerted effort between policy makers and researchers. Requirements for model development need to be defined, resources for research need to be mobilized and research needs to be managed and maintained. Given the nature of some of the problems addressed above, the time pressure on providing evidence for major freight-related policy decisions (e.g. on global climate action matters) is considerable. This will hopefully help to drive freight modelling research forward.

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