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Generation of logistics networks in freight transportation models

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Abstract This article analyzes the concept of logistics networks in the context of behavioral freight transport modeling. Starting from the basic definition of networks, the different perceptions of networks in transportation science and logistics are worked out. The micro–macro gap, as a main challenge in freight transport modeling, is explained by the existence of logistics networks on a meso level. A taxonomy of modeling methods dealing with logistics networks is defined, based on two characteristics: the changeability of networks within models (fixed, partially variable and variable networks) and the form of cost functions mapped (economies of scale, constant average cost, and diseconomies of scale). For each category, different possible modeling methods and their application in existing freight transport models are discussed. A special focus is placed on methodologies and models that map variable networks.

Keywords Logistics networks · Behavioral models · Freight transportation models · Commercial transport · Micro-macro gap · Freight planning

Introduction and motivation

The importance of freight transportation and logistics for politics has increased during the last decades: Freight constitutes a growing proportion of overall transportation, and efficient logistics services are more and more considered a key requirement for economic development.

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To analyze the effects of policy measures in relation to commodity transportation, commodity transport models are required. If the political measure in question influences the behavior of logistics actors, the model should explain logistics decision-making and be sensitive to the policy.

However, for many decades, the state-of-the-art in modeling freight transport was far behind passenger transport modeling. First major progresses have been achieved by approaches in which flows of goods and passengers are routed over a multimodal transport network (Sheffi 1985; Nagurney and Dong 2002). Later refinements incorporate the operating program on infrastructures and further logistics activities, such as warehousing or unitization (Tavasszy et al. 1998). In recent times, a couple of studies have been published that try to incorporate more logistical details into transport models by focusing on the microscopic level (Wisetjindawat et al. 2007; De Jong and Ben-Akiva 2007; Ramstedt et al. 2008; Maurer 2008; Liedtke 2009; Friedrich 2010; Holmgren 2010; Roorda et al. 2010; Samimi et al. 2010). Most of these developments are described and analyzed in a couple of overview papers (De Jong et al. 2004; Tavasszy 2006; Chow et al. 2010). It turns out that the models and model-concepts differ significantly with respect to the logistical aspects covered and the way they are mapped.

To be able to classify these existing approaches and identify useful methodologies for including logistical aspects in transport models, we want to emphasize a new point of reference: logistics networks. By definition, a logistics network is the core decision-objects of an individual firm (micro or meso level of the transport system)—a set of nodes and transport connections that is subject to the planning process of that firm. Logistics networks differ from physical transport networks which are rather provided and planned by public authorities and which serve to satisfy mobility demand of the whole economy (macro level of the transport system). Logistics networks are of high importance for behavioural freight transport modeling.

This paper gives an overview on how logistics networks are represented in existing freight transport models. A special focus will be placed on some recent modeling activities of the authors that were driven by the idea of mapping logistics networks in space which are subject to structural adaptations.

It is organized as follows: After these introductory remarks, the concept of networks is presented in detail, both from a transportation and from a logistics perspective ("Networks in transportation science and logistics" section). Then, a taxonomy of methods is developed that focuses on how freight transport models deal with logistics networks and possible reactions (changes) as an answer to changed environmental conditions ("Taxonomy of methods for the modeling of logistics networks" section). For each model category we will provide different possible modeling methods and their application. "Conclusion" section briefly concludes the paper.

Networks in transportation science and logistics

Networks are discussed in many different disciplines and contexts. In mathematical graph theory, a network corresponds to a labeled directed graph without isolated vertices (Neumann and Morlock 1993). Other authors define a network simply as a set of vertices and a set of nodes (see Wasserman and Faust 2008 or Newman 2010), which corresponds to the definition of a graph. Some disciplines—especially the social sciences—focus on the systemic aspects of networks. They identify a close similarity between a network and a system as perceived in system theory (Bossel 1994). Thus, according to the latter perception, a network is a system that can be modeled mathematically as a graph and which possesses mechanisms for its internal organization. For the definition of logistics networks, we will build on this last definition. On the level of firms a logistics network constitutes a planning object of a certain economic actor. Transportation science on the other hand traditionally focuses on the utilization of physical infrastructure networks by all users—the macro level of the transport system. Starting from the identified different understandings of networks in transport planning and logistics, the research questions of this paper are stated at the end of this section.

Networks in transportation science

Transport policy makers and traffic engineers are in charge of providing and optimizing the physical infrastructure supply for all firms and households. That is why physical transport networks are the main focus of infrastructure planners. In physical transport networks there are two types of nodes: there are junctions and crossings, and there are access-nodes (for instance: terminals, stations, connectors). The links of a physical transport network are, for instance, railway lines or roads.

Classical transport models usually assume this network as given (depending on a certain planning scenario); vehicle flows are then assigned to this network by mapping the routing decisions. Since there are strictly increasing user costs on the links, expressing congestion, iterative algorithms can be used to calculate the user equilibrium.

This basic network modeling approach has been extended to super- and hypernetworks. Supernetworks can be described as a combination of several physical networks. Abstract hyperlinks composing a hypernetwork represent aggregated links of a network (see Cascetta 2009). Additional decisions—aside from route choice in the physical networks—like mode choice can be modeled as a route choice on such a hypernetwork (see Sheffi and Daganzo 1979 for more information). The supernetwork and hypernetwork concepts are closely related and are used as synonyms (Sheffi 1985).

Networks in logistics

Logistics as a scientific discipline and an economic activity focuses on networks of individual companies or associations of companies. Logistics networks are more likely to be logical networks: Links represent transportation service agreements or scheduled services encoded in timetables. They do not necessarily correspond to individual physical infrastructure links. Nodes of logistics networks are generally facilities of private firms. We propose the following definition for logistics networks:

Definition A logistics network is the set of nodes (for instance, warehouses or transhipment points) and transport connections resulting from and being subject of a planning process of an economic actor or association of actors deciding together.

The scope of the underlying planning problem can be described through a set of commodity flows. Logistics network decisions include both the usage of given networks ("routing of freight flows") as well as decisions concerning the design of those networks ("network design"). The definition of logistics networks is a microeconomic one since it is oriented towards a decision-making entity—an individual company or an association of companies. The scope of a logistics network is defined by a planning horizon and planning problem. Note that our definition is slightly different from the engineering one that also includes networks in which many actors that have no common optimization commitments may participate (see for e.g., “Interlog” networks in Gudehus 2005).

Two types of logistics networks can be differentiated by looking at the function of the nodes: In the nodes of warehousing-oriented logistics networks, articles are stored and buffered as well as repackaged and commissioned. Nodes of transport-oriented logistics networks only consolidate and deconsolidate individual shipments. With the rise of contract logistics, pure transport-oriented networks are more and more vanishing.

In general, logistics networks are interlinked (entangled) with other networks. A distribution network with nodes that have warehousing and commissioning functions, for instance, might use transportation services provided by transport-oriented logistics networks. The ramp of a shipper is an external node of a production logistics system as well as an external node of a transport service provider’s network. The coordination between different networks is ensured by local and global market interactions (see Liedtke 2006 and Sjöstedt 2004). Since logistics networks are often directly and indirectly interconnected, the overall integrated structure can also be described as a network similarly to the example in Gudehus (2005). The overall structure is not a logistics network according to our definition above. However, within this overall network there might be situations in which different logistics networks are perfectly aligned as a result of local coordination processes. Liedtke (2006) provides the example of a regular operational structure that comprises a forwarding agency, an independent trucker, other trucking companies, and a couple of shippers. Because of the lack of an economic actor or economic institution in charge of constructing or improving this operational pattern, such structures are named meso-structures.

In the long run, logistics networks change their structure. These changes could be induced or at least influenced by policy measures. A freight model that maps variable logistics networks is useful for assessing transport policies aiming at changing logistics behavior, similarly to the activity-based models that allow for activity rescheduling. For the remainder of this paper it seems to be appropriate to distinguish between short and long term reactions:

Short term reactions relate to changes of the usage patterns of networks. These changes are similar to the changes of traffic flows that are routed over a physical transportation network.

Long-term reactions are changes of the structure (topology) of networks, market entries and exits, and the emergence of new businesses (new types of networks). Structural changes could be mapped by using the whole palette of optimization tools dealing with non-convex and combinatorial optimization (e.g., Daganzo 2005 or Domschke 2007). The evolution of networks over time (“dynamic networks”) has rarely been analyzed so far (Gudehus 2005, p. 576). The long term reactions are congruent to the economic perception, which calls them long-term dynamics. The latter is generally associated with market entry and the existence of firms and with the emergence and decline of technologies. See, for instance, Stiglitz (1990) or North (1991) regarding the notion of dynamic efficiency, Schumpeter’s concept of creative destruction (Schumpeter 1952) and Kondratjew (1926) on technological cycles. Note that all these theories explicitly take into account economies of scale.

Thus, mapping all sketched types of long-term changes needs dealing with non-convexity. In fact, economies of scale are omnipresent in logistics. The long-term cost of warehouses or terminals is declining since with higher throughput more automation can be used (see Gudehus 2005) on decreasing average warehousing costs. On the links, different shipments can be consolidated on one vessel, and frequency increases together with transport volume.

Challenges in freight transport modeling

On their way from the producers down to the consumers, commodities follow a complex path through a sequence of logistics facilities, where they may change their characteristics (consolidation, deconsolidation/unitization, and combination with other commodities) and the mode of transport. This path often does not correspond to the shortest path in terms of distance. The reason for the deviations lies in the fact that commodities themselves are not decision-making entities. Instead, some economic agent has to organize transport and transshipment. Since each economic agent wants to make profit, they must organize these activities in an efficient way. That is why logistics networks are set up. Logistics networks have their "raison d'être" in saving warehousing and transportation cost by combining shipments (Groothedde 2005; Bryan and O'Kelly 1998). The grouping of articles in packages and of packages to palettes, etc., fulfills cost-saving purposes and leads to the emergence of logistics networks. The path of the individual commodity is determined by considerations for the overall network. Logistics choices are governed by finding system optima for groups of shipments; they do not follow the logic of finding the optima for individual shipments.

Transport and logistics supply in this context are services provided by these logistics networks using the physical infrastructure networks. A company having demand for logistics services can either run its own logistics network or buy services from another company (logistics service providers). A logistics network supplies logistics services for shippers or other logistics networks. So, there can be several steps from shippers' logistics demand to demand for infrastructure use.

The phenomenon of logistics networks is the reason for a challenging dilemma in freight modeling—the micro–macro gap. Logistics networks represent a stratum of the real

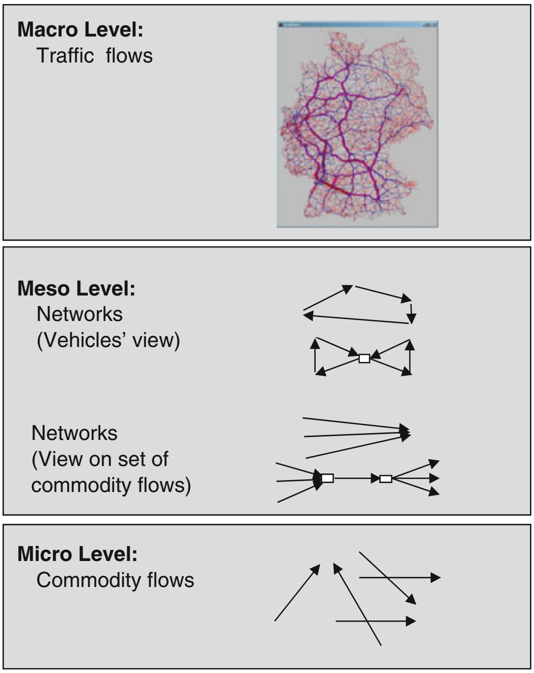

Fig. 1 Visualization of the macro–micro gap in freight transport modeling. *Source*: Friedrich (2010)

economic system situated between the micro level (commodity flows) and the macro level (vehicle flows) of the transport system. The importance of this meso level to the understanding of freight transport has already been pointed out by many researchers (for e.g., Sjöstedt 2004). The idea is represented schematically in Fig. 1.

Figure shows the micro, meso, and macro levels of freight transportation. The macro level on the top corresponds to the perspective of transportation planners and policy makers. This level deals with vehicle flows in infrastructure networks. Logistics activities on this level are expressed as aggregate indicators, such as market shares by segment or container throughput of ports.

The micro level corresponds to (microscopic) commodity flows between senders and recipients. These flows are displayed as arrows in space. When these flows are combined, logistics networks are formed; they represent the meso level.

Since commodity flows are generally not congruent with vehicle tours (that can be aggregated to vehicle flows on the macro level), there is a mismatch between commodity flows at the micro (firm) level and vehicle flows on the infrastructure. Therefore, it is necessary to understand the meso level of logistics networks to establish a connection between economic decision-making and phenomena observed at the macro level. A main question for freight transport modeling, in our opinion, is how to handle logistics networks on this meso level. Against this backdrop, the following open-ended questions for transportation systems analysis arise:

- How is it possible to simulate a high number of logistics networks for the purpose of transport modeling?
- What possibilities are there to consider logistics networks in an aggregate way within a transport model?
- And finally, could it be possible to map logistics networks in such a way that they react to changing environmental conditions (for instance, to map changes in logistics networks as a response to policy measures or economic developments)?

The following model taxonomy attempts to give a systematic overview of the state-of-the-art modeling methods in order to give answers to these questions.

Taxonomy of methods for the modeling of logistics networks

In this section, we analyze how existing freight transport models map logistics networks. The overview is oriented more towards methodologies than models. It is not exhaustive with regard to the selection of models, leaving more space for discussing models that explicitly map logistics networks.

To distinguish between different transportation models, model characteristics can be taken into account; they can be found in Bossel (1994) or transport modeling textbooks (for e.g., Ortùzar and Willumsen 1990). They are classically grouped into pairs of opposites: explanatory versus descriptive models; incorporation of optimization tools versus iterative algorithms; tour-based freight models versus flow- and shipment-based models; micro versus aggregate models. Finally, different models may map different logistics reactions (tour-construction, shipment size choice, mode choice, supply path choice, location choice…). In the present paper that focuses on logistics networks, we will concentrate on the following two characteristics:

- the changeability of logistics networks within the model and

- the form of cost functions for links and nodes used within the models: increasing, constant or decreasing average costs with respect to the throughput of goods—or simply speaking: economies vs. diseconomies of scale.

The first characteristic refers to the ability of models to map changes in logistics networks and thus, changes of the transport supply for the shippers and of the demand for the infrastructures: Models that generate fixed logistics networks (fixed topology, fixed attributes) have a purely descriptive character; they could serve to generate a fixed background load in a transport model. Models with partially variable networks deal with logistics networks that have a fixed topology but flexible attributes; these networks are sensitive to short-term reactions. Models with variable networks are suitable to map long-term dynamics which includes structural adaptations. For models that aim to map behavioural responses in logistics this is especially important (also see Heinitz and Liedtke 2010).

The form of the cost functions has been selected as the second important distinguishing characteristic because of its influence on model-construction and solution-procedures—in economics and in logistics: Economists understand long-term dynamics as a result of economies of scale. In logistics network planning, there could be different optimal network configurations, if there are decreasing average costs (Daganzo 2005). Increasing average cost is the standard assumption of most Industrial Organization models. It is also a core assumption of the (neo) classical model. Algorithms that yield a global optimum can be employed to optimize logistics networks and to determine the usage patterns of transportation networks.

The following overview focuses on transport models that are naturally positive models. Normative logistics models for the optimization of individual logistics structures are only considered implicitly.

Models of fixed logistics networks (fixed topology, fixed attributes)

Modeling fixed logistics networks mainly consists of the generation and location of logistics networks in space. In this context, logistics networks can be generated directly or using Monte Carlo simulation. The common purpose is to reproduce existing logistics networks as well as possible. In some models, the simulation of fixed logistics networks might be initiated in each planning scenario (or in different computation iterations); in some models it is only a first step preparing the modeling of partially variable logistics networks (see later on in “Models of partially variable logistics networks” section).

Direct Generation (by hand and/or data-based)

Logistics networks can be generated directly according to the knowledge of the modeler. For this purpose, an extensive data survey and the study of secondary data sources are necessary. This method is used, for instance, to deal with individual networks or generators of freight transport flows, e.g., ports. To capture future developments (for instance, when setting up a model for a national master plan for the next two decades), it is necessary to predict the development of the logistics networks. This is done by collecting data or by constructing scenarios on possible future new construction or capacity extensions.

The establishment of a physical and logical multi-modal network as the first step of hypernetwork approaches in freight transportation (Jourquin and Beuthe 2001, 2005; De Jong and Ben-Akiva 2007) is a typical example of direct network generation. In these hypernetwork approaches, the direct generation could be subdivided into two stages: First, the physical networks are specified. Then, transport connections are enabled by defining intermodal connections and by stating further constraints. Note that once such a network has been generated, a routing of freight flows on the given and fixed logical network can be performed (see section on partially dynamic networks).

Random generation of networks

To generate logistics networks randomly, two methods are well established: Monte Carlo simulation and entropy maximization.

In Monte Carlo generation, the microscopic entities are selected or generated and located in such a way that the distributions or samples are reproduced consistently with the aggregate indicators. In a guided Monte Carlo simulation (see, for e.g., Liedtke 2006), the random process is additionally influenced by the networks which have already been generated.

As an alternative approach to the sequential Monte Carlo algorithms, the entropy-based approaches from passenger transport modeling could be used. They generate the most likely micro distribution respecting observational constraints (see Pritchard and Miller 2009).

Monte Carlo simulation is used in many micro freight-transport models: Liedtke (2009), Friedrich (2010) and Wisetjindawad et al. (2007), for instance, place manufacturers and transport companies in space using Monte Carlo algorithms ("synthetic population"). De Jong and Ben-Akiva (2007) generate firm-pairs on the basis of aggregate freight flows.

Once the synthetic firms have been generated, they can be interconnected, and thus the sender–recipient connections are set up. Liedtke (2009) generates value-adding networks using a guided Monte Carlo algorithm. Wisetjindawad et al. (2007) generate connections between producers and recipients based on a discrete choice model and a random number generator.

Monte Carlo simulation or entropy maximization can also be used to generate tour networks: Lohse et al. (1997) and Wang and Holguín-Veras (2009) generate tour patterns using the entropy-maximization principle. The WIVER model (Sonntag 1996) uses statistical simulation in connection with the savings heuristic from Operations Research. This method is a combination of a random process and an optimization heuristic.

Models of partially variable logistics networks

In this model category, the network nodes and links remain unchanged, only attributes, for example the flows or frequencies on the links of the networks, are subject to changes. Such partially variable networks can map short term reactions on changed environmental conditions.

Three approaches can be distinguished looking at the assumption for the cost function of links and nodes of a logistics network: (i) having diseconomies of scale, (ii) having constant average cost, or (iii) having economies of scale.

Increasing average cost ("diseconomies of scale")

It is well-known that the occurrence of increasing average costs (for instance, due to congestion or transaction cost) leads to the formation of the perfect competition equilibrium in markets and the user equilibrium (i.e., a Nash-Cournot equilibrium) in networks (see Ortuzár and Willumsen 1990).[1] Inversely, this means that, in order to ensure the existence of a unique equilibrium in a market or concerning the flows on the links of a network, it is crucial to base the model construction on the assumption of increasing average costs and to neglect fixed cost to a certain extent.

Nagurney (2002) introduces the “variational inequality” (a network equilibrium condition) into logistics. Nagurney (2010) formulates a combined oligopolistic market equilibrium (Nash-Cournot equilibrium) and logistics network assignment equilibrium (Wardrop’s first principle Wardrop 1952) based on the variational inequality. The approach is based on two assumptions: (i) the cost-function of capacity-provision and the operating cost exhibit increasing marginal costs and (ii) there is no fixed cost. Since the capacities are adjusted in each iteration according the flows on the links, long-term increasing average costs are assumed. Long-term market developments are only considered partly as firms can be removed from the initial set, but new ones cannot emerge.

Constant average cost/activity-based costing

In this approach, the network topology has to be predefined in another modeling step and it is then assumed as given and fixed. Activity-based costing or standard cost values are applied to calculate the cost (or the benefit) of reloading, storing or unitizing commodity flows in logistics nodes. Because of the activity-based costing, the benefits of bundling commodity flows are only mapped in a weak fashion. The SMILE model (Tavasszy et al. 1998) is an example of an aggregate variant of this approach. The model’s core determines a sequence of nodes for each OD relation, in which the commodity flow might change its nature and means of transport. The logistics nodes do not necessarily have a real-world counterpart. Instead, they represent the sum of the latently existing logistics services in each region without any capacity restriction.

Decreasing average cost (economies of scale)

To consider economies of scale in logistics networks the consequences of attribute changes on average costs have to be mapped. De Jong and Ben-Akiva (2007) propose a discrete-choice modeling framework to determine (i) shipment sizes and (ii) flows through an intermodal transport network that has been generated “by hand”. In this approach the network attributes are updated continuously and flows are rerouted on the network. By doing so, the effects of consolidation can be mapped explicitly. In certain cases it can be imagined that links and nodes can “run dry” with the consequence that the average cost increases enormously. In the real world this means that those links and nodes would be closed. However, the emergence of new structures is not part of the described modeling approach. This leads to the model category of “variable logistics networks”.

Models of variable logistics networks

In this model category, logistics networks can change their topology. Nodes are added, upgraded or removed; connections emerge or are discontinued. In a market simulation

[1] Increasing average cost generally implies: marginal cost > average cost; additional condition for perfect competition: many competitors (the actions of each active company have no or only little influence on the aggregate price level).

"inefficient" networks might drop out of the market and, conversely, new networks might emerge if demand increases. Long-term dynamics and economies of scale are described. We found three approaches of mapping variable logistics networks (i.e., changes in the transport supply for the shippers): market-simulation using agent-based models, adapted optimization of logistics networks, and finally the analytical determination of the long-term market equilibrium.

Market simulation

A logistics market simulation combines the behavior of logistics agents (i.e., the optimization of their networks) and market interactions. A market simulation could map short-term dynamics or long-term dynamics, including market entry and exit. Using agent-based modeling methods, complex economic strategies, dealing with market entry and price-setting could be implemented, too. Agents can also experience the consequences of different strategies and accumulate knowledge of their environment.

Changes in tours can be considered short-term or long-term reactions: They do not involve investments but there are often long-living tour-structures and contracts (the cost of establishing a contract or a tour can be considered a fixed cost). In terms of logistics networks' changes, tours represent partly variable networks, if there are changes of the attributes of links. If links are added or removed, we deal with variable tour networks. The problem of shipper-carrier interaction in the context of tours is often addressed by simulating auctions: In a conceptual paper, Roorda et al. (2010) suggest combinatorial auctions to map the choices of shippers and logistics actors. The INTERLOG model by Liedtke (2006) was principally based on a simulated auction in which forwarders calculated their offers based on either full or marginal costs. In both models, a large number of carriers, including their transport resources, are latently existent. Coordination between shippers and forwarders is performed by simulated auctions. Tours are determined using solution procedures taken from Operations Research (insertion and meta-heuristics). In a critical resume of his own work, Liedtke (2009) recapitulates that a combination of simple auctions with optimization alone is not an appropriate solution to address the formation of logistics networks: If carriers base their decisions on a full-cost allocation schema, they will have difficulties entering (into) the market because a new entrant would never be able to give competitive offers. Combinatorial auctions as proposed by Roorda et al. (2010) have to be simulated in order to allow carriers to acquire a contract together with a suitable return cargo. In order to overcome the weaknesses of market simulation with partial market entry and exit, the basic approach must be extended.

One option might be to implement market entry and exit as well as price-setting strategies in the form of a trial-and-error process. In such a world, only the fittest species (in terms of price-setting strategies and network design) would survive. This approach could be extended by including more and more intelligence: Price setting could be based on average cost and be varied according to the market price level (temporary scarcity of demand or supply, imparity of flows). Agents could appraise market-entry decisions and capacity-extension decisions by comparing average market prices and their potential future costs. Such decisions are examples of forward-looking decisions: The agents ask themselves what would happen after realizing a decision which alters the network topology. The modeling of such complex strategies is the objective of the next category.

Adapted optimization

To model emergence and behavioral reactions of complex logistics networks, normative models can be used. However, when applying normative models for descriptive purposes additional assumptions are required to represent the behavior of economic actors appropriately. An economic actor behaves rational under certain circumstances (constraints) as well as concerning its environment of uncertainty. Furthermore, costs of information procurement and processing have to be considered when modeling the behavior of economic agents. This refers to the concept of bounded rationality (Simon 1996).

Therefore, in most cases procedures from logistics optimization (normative models) need to be adapted to match this real-world behavior. Parameters and constraints have to be added that are not included in traditional logistics optimization models and solution procedures (heuristics) have to be selected accordingly. When it comes to decisions altering the network structure, the consequences on future operations and future decisions should be anticipated (forward looking) instead of solving the whole optimization problem. In any case, the models have to be validated by comparing the results to reality.

The SYNTRADE model of Friedrich (2010) is an example of a bounded-rationality logistics-network model. It maps the emergence of logistics networks in food retailing in Germany using adapted logistics optimization. Typical decision procedures and product specifics of the sector are included in the optimization procedures. Two logistics decisions are mapped: The first one is the optimization of the warehouse structure (logistic network structure), including stratification (existence of a central warehouse level), number of regional warehouses, location and allocation of points of sale. The second one is the choice of supply paths for the commodity flows, including delivery frequencies and the choice between alternative logistics networks. A forward-looking algorithm for the warehouse structure decisions explicitly considers the possibility of changes of the supply paths. It maps the situation of a high-level logistics manager who anticipates the upcoming decisions of the lower-ranking purchasers undertaken on a day-to-day basis.

The model assumes the turnover and the locations of the points of sale (business activity) as given and fixed. The maximum scope of a logistics network of the retailing companies is defined by all commodity flows connected to the business of a retailing company. Which flows are routed over the own networks depends on the supply path decisions and hence, on the alternatives of logistics networks.

The model parameters are calibrated based on logistics networks of five retailing companies. The remaining retailing companies have been used for validation.

Figure 2 shows the locations of all warehouses in the food retailing sector in Germany. The left side shows the real location pattern and, on the right side, the model results in SYNTRADE are depicted. The two distributions are highly homomorphous, both on an aggregate and on a company level.

Analytical calculation of the long-term market equilibrium

Instead of carrying out simulations, the market equilibrium can be calculated analytically. Micro economics has studied a broad palette of market equilibria: Depending on the firms' cost functions, the elasticity of demand, as well as market entry and exit barriers, different analytical expressions for the number of active firms and the prices charged to the customers can be deduced.

In the case of homogeneous goods, the Cournot oligopoly can be formulated. The quantities produced by the individual firms result from game-theoretical considerations.

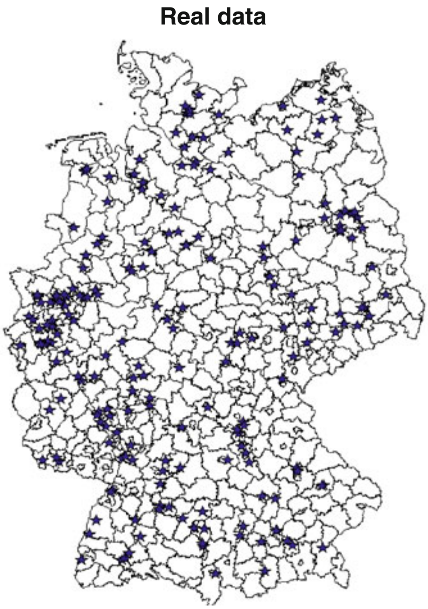

Fig. 2 Warehouse locations—real locations versus model results of SYNTRADE. *Source*: Friedrich (2010)

The market price depends on marginal cost, demand behavior/elasticity, and number of competitors. If market entries and exits are possible, the number of active firms is determined in such a way that all active firms just break even (so-called Marshallian market equilibrium (Marshall 1920; Mas-Colell et al. 1995, p. 316 ff).

However, freight transport markets deal with heterogeneous commodities. Heterogeneity results from the spatial dimension (each transport-relation is a separate market), and because of the heterogeneity of contracts (contract duration, degree of outsourcing, heterogeneity concerning size and shape of the shipments, regularity). Thus, there is not only price competition but also product differentiation. Prices instead of quantities become action-parameters of transport companies. In addition, due to economies of scale in logistics networks, oligopolistic actions have little effects. This is why another type of competition equilibrium might be more appropriate—monopolistic competition.

Monopolistic competition under the assumption that consumers act according to a constant-elasticity-of-substitution utility-function have been studied by Dixit and Stiglitz (1977) giving the basis for many Spatial general computable equilibrium models (SCGE) such as Bröcker (1998) or Ivanova et al. (2007). Some of the SCGE models determine the number of active firms endogenously, for instance RAEM 3.0 (Ivanova et al. 2007). SCGE models are used for the purpose of economic assessment but they cannot reproduce choice-behavior exactly according to logit functions. Note that the ratio between fixed and variable cost has a strong influence on the equilibria outlined above. This is not the case when describing consumers' behavior using logit functions.

Oligopolistic competition with product differentiation and consumers acting according to a logit choice function has been studied by Anderson and de Palma (1991). When using their formalism—which is similar to the deductions of Dixit and Stiglitz (1977)—some elements of oligopolistic competition remain, i.e., the possibility to increase profits by strategically increasing prices. However, assuming strong economies of scale, elastic demand and spatial competition the oligopolistic elements are rather weak and the equilibrium number of active firms m can be described by the following expression:

$$m = \frac{D}{\alpha} \cdot \frac{\mathrm{d}Ac(x)}{\mathrm{d}x}$$

with α homogeneity parameter of the discrete choice model, D total demand, $Ac(x)$ long-term average cost function of a logistics network in function of its turnover x.

This expression can be reproduced by two other completely different approaches (Carrillo Murillo 2010).

The first is the solution of an optimization problem. The term to be minimized is a combination of an entropy term as introduced by Wilson (1970) and total cost—the so-called free economic energy (FEE) minimization. FEE minimization reflects two characteristics of freight transport systems. On the one hand, there is taste for heterogeneity, lacking information and the tendency that big structures are destabilized just because they are big and economic actors are curious. These factors lead to entropy generation. But, on the other hand, actors and groups of actors in logistics seek to share fixed costs and realize synergy effects—cost minimization. Alternatively, the market equilibrium could be reproduced using the master equation (Weidlich 2000). This approach maps the tendency of operators of transport networks to grow, to poach customers from competitors and to realize economies of scale. The formation of monopolies is limited because of the desire for variety. The equation above is valid for companies operating logistics networks as well as for spontaneously emerging associations of actors realizing agglomeration benefits so-called "clusters" or "colloidal structures" according to McFadden (2007). Note the similarity between FEE minimization and the approach of Fisk (1980) to the computation of network equilibrium assignment under the presence of heterogeneity: In the approach of Fisk (1980), users of a network minimize an expression composed of cost and entropy. In an iterative procedure, a stochastic traffic flow equilibrium results on a network whose structure is given and fixed. The FEE approach maps logistics choices in a similar way, but in addition the market produces an optimum number of alternative choice options endogenously—the colloidal structures.

In transport modeling, the equation above can be used as a functional form in an econometric explanatory model. Once the parameters of the model have been estimated, it is possible to place logistics networks in space or to determine the effects of changes in environmental conditions. Carrillo Murillo (2010) determines the impact of public investment grants on the development of hinterland terminals. Carrillo Murillo (2010) also analyzes regions in which investments into terminals might be especially promising.

Conclusion

In transportation science, increasing attention is paid to freight transport, which takes up more and more of the capacities of the infrastructure networks, and which is an increasingly crucial factor for economic development. However, the integration of freight into transport models is very difficult. One reason for this is the existence of logistics networks, which have the effect that commodity flows do not follow the shortest (in terms of physical distance) paths from their sources to their destinations. We have shown that transport models use different approaches to incorporate logistics networks. Three main categories have been identified: approaches modeling fixed, partially variable, and variable networks. In the first category, structures are assumed to be fixed; they are generated synthetically as model input or they just represent the existing or projected real-world structures. Approaches modeling partially variable logistics networks assume fundamental network topologies to be given and fixed but network attributes (such as link-load or frequency) to be flexible. Finally, approaches modeling variable logistics networks explain network topology and attributes endogenously.

In the first category Monte Carlo methods can be used or the structures are placed "by hand". Approaches routing flows over given logistics networks belong to the second category. While they are used to model freight transportation on a national level, these approaches are not completely behavior-sensitive, since they lack important reaction mechanisms—structural changes. There is a high danger that demand and supply structures in such a model are not consistent and the modelers themselves often define the logistics networks by hand which might directly influence project appraisals.

Therefore, approaches from the third category seem to be the most attractive, but they are also the most difficult to implement and still far away from practical application in policy and transport-infrastructure assessment. The major reason for the challenges is that mapping structural changes requires the assumption of economies of scale for those systems. By doing so, we are dealing more and more with non-convex optimization problems and with dynamic market interaction including market entry and exit. Furthermore, non-convex optimization may require the application of complex solution procedures within a multi-agent environment. Three existing and tested approaches have been identified that model behavior-sensitive variable logistics networks:

- The first is market simulation. To stabilize this simulation, market feedback in the form of overall market prices should be incorporated to give signals for market entry and exit as well as for price setting. To model the dynamics of complex logistics networks, forward-looking decisions have to be represented. Local optima concerning the topology of logistics networks can only be avoided with a large and forward-looking scope for decision-making.
- This is the focus of the second sub-category which adopts procedures from logistics optimization to map reality. The presented model SYNTRADE demonstrates this approach for logistics networks in food retailing. Such models are suitable if details on logistics networks are of interest.
- In the third sub-category an approach was described that uses the concept of monopolistic competition to explain existing market equilibria. The model can be calibrated empirically. For certain analyzes, transport market models based on oligopolistic competition could be used.

Different approaches to modeling logistics networks are currently used in transport modeling. For practitioners it is advisable to start with a well-established approach routing flows over given logistics (hyper-) networks and include aspects of variable logistics networks to improve the behavioural sensitivity of models. With regard to variable networks, further research is necessary.

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