Handbook on city logistics and urban freight

Chapter 3: *Overview of urban freight transport modelling*

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Introduction

The urban freight transport system has many unique characteristics and concerns that make it stand out from national or global freight transport systems. Cities are places of mass consumption, where logistic processes serve the urban fabric as a place of destination for retail goods and construction materials. Urban freight involves also first-mile transport for manufactured goods, waste and consumer-to-consumer (C2C) shipments. Last-mile transport usually ends at the consumers' homes or the place where they pick up the goods for personal use; at an intermediate stage, the freight will pass through warehouses, cross-docking centres or fulfilment centres. It is here where product flows are broken down into individual consumption units and mass individualization of society becomes most visible. Also, as distances are usually short, the modes of transport exclude the typical long-distance transport by air, sea and rail and include active modes such as walking and cycling. Commodity mixes include mostly consumer goods traffic, service traffic and construction materials, whereas the share of industrial goods is low. Freight delivery traffic mixes intensively with other purposes of transport inside residential, business and recreation areas. There is fierce competition for urban space, extending well beyond that needed for transportation alone and including parking, waiting, (un)loading, manoeuvering, registration, storage, handling, etc. The high population densities introduce additional risks to the safety and health of citizens. Each of the stakeholders involved in these activities is powerful, in different ways. As the urban consumer is at the end of the chain, their demands are followed by the entire supply chain. Retailers and service providers are parts of big conglomerates and, with their decisions, can make a large impact on city liveability. This concatenation of stakeholder interests and powers makes the urban freight transport system a challenging one to describe in models. The engagement of stakeholders is a separate line of research: Browne and Goodchild provide an overview in Chapter 15 of this Handbook.

Urban freight models generally require integrated modelling approaches that combine both optimization and simulation, such as dynamic flow simulation and multi-agent systems

(Taniguchi et al., 2003) The main function of urban freight transport models is to provide comprehensive information to all stakeholders about the current and expected performance of the system under different future social, economic and technological scenarios: the models are used to assess the effects of these scenarios (Crainic et al., 2009; Comi et al., 2014; Holguín-Veras et al., 2018). At their core, these models traditionally focused on the intensity of transport services within and around the urban area, to support long-term investments and policies. Nowadays, the models provide numbers needed for the design of infrastructural provisions, new services, business models and even governance arrangements between stakeholders. More and more models are also becoming a basis to support experimentation with socioeconomic and technological innovations (like crowd-shipping platforms) in multi-stakeholder, value-driven innovation processes. Models are also becoming a component of urban traffic control towers for real-time flow management. Finally, we see that the notion of cities as places of mostly on-demand, last-mile movements is slowly becoming obsolete. Consumer-to-consumer trade is growing and the circular economy will amplify return flows. The above developments imply that the field of urban freight transport modelling is dynamic and innovating fast.

Literature on modelling urban freight processes is overwhelmingly normative in nature and focuses on optimization of decisions. Even for applications in city logistics, much modelling that relates to company-level decision making uses operational-research-based optimization as the main tool. Crainic et al. provide an updated overview of operations research for planning and managing city logistics systems in Chapter 10 of this Handbook.

In contrast, descriptive approaches, such as discrete choice modelling, aim to provide a picture of representative decision behaviour for a previously defined population of firms (e.g. all firms in a city). Both model types have existed next to each other and are sometimes used within one modelling framework. Our focus in this section is on descriptive and predictive models as they are statistically validated as a (sufficiently) truthful representation of urban freight processes – which is not necessarily the case with optimization models.

The aim of the current chapter is to provide an overview of the key recent developments in urban freight modelling, with a focus on the latest research and innovation directions. In that sense, it introduces the subsequent chapters (Chapters 4, 5 and 6) in this section. These present three examples of the most recent modelling developments in urban freight demand. Each example deals with one of the particular levels of urban freight demand models shown in Table 3.1: production and attraction of freight trips, the simulation of freight patterns, and vehicle flow. Sánchez-Díaz and Castrellon-Torres (Chapter 6) provide a contemporary overview of freight demand generation models in the urban context, predicting freight and/or vehicle flow using establishment data. Their chapter also discusses the linkage to microsimulation agent-based models. Comi and Delle Site (Chapter 4) present a forecasting model for restocking activity and tour planning for the retail sector in the urban context, representing logistics functions explicitly. Sakai et al. (Chapter 5) present a state-of-the-art multiagent simulation model for city logistics. Logistic agent behaviour is simulated across different dimensions of decision making, with a focus on the choice of carrier and vehicle activity

The remainder of this chapter is organized as follows. The second section presents a conceptual framework for freight modelling to help position the work on freight modelling presented in this Handbook. The third section gives a short overview of different generations of urban freight models, and how they have evolved from the conventional four-step and operations research models into the multistakeholder, multiobjective simulation models in use today. The fourth section summarizes the key new challenges in urban freight transport, elaborates on the resulting changes in user environment and model requirements, and discusses how these requirements are being translated in a new generation of urban freight transport models. Finally, we introduce the subsequent chapters of this section on urban freight modelling.

Conceptual Models of Urban Freight

Transport services serve a demand that is derived from various supply chain activities in between consumption and production, including distribution, packaging, inventory management, etc. In order to predict transport flows in a way that they relate to the real-world economy, this background needs to be understood. Models do not need to model all details, but merely effectively summarize real-world activities using aggregate structures, and reproduce the results of logistics decision making across different functional layers in the supply chain. Real-world decision-making structures in logistics are complex. Riopel and Langevin (2005) mapped and categorized logistic decisions in relation to transport. Figure 3.1 shows in a stylized way how these decisions are interconnected.

The importance of their study lies in that it provides a comprehensive conceptual model rooted in supply chain management, which mathematical modelling efforts can use as a starting point. Next to eight transport-focused decision problems, they also identified 40 contextual decisions that directly or indirectly influence these eight transport decisions which vary according to specific market characteristics. The transport-related decisions include:

- Transport modes.

- Types of carriers (own account or for hire, specialization, etc.).
- Carriers.
- Degree of consolidation (e.g. hybrid channels or combined).
- Transport fleet mix.
- Assignment of customers to vehicles.
- Vehicle routing and scheduling.
- Vehicle load plans.

The relevant contextual decisions are the ones that shape the demand for transport, span all areas of supply chain management, and can be found in the following areas:

- Strategic level decisions, e.g. setting customer service decisions.
- Tactical level decisions, including physical facility network design (e.g. number and location of distribution centres) and communication and information network design.
- Operational level decisions, including demand forecasting, materials handling, procurement and supply management, production, product packaging, inventory management, order processing and warehousing.

A full simulation of all these decisions to replicate all the individual steps that firms in the real world go through would be a daunting task. It is also probably unnecessary, as the main challenge in modelling is to identify the smallest subset or aggregate of decisions which provides a sufficient representation of reality. As a result, decision-support models that integrate this entire spectrum of decisions do not exist and probably never will. Models always focus on subsets of the logistics systems, on specific relations or on an aggregate of multiple decisions. They will thus summarize or ignore many details in this system, resulting in varying degrees of sophistication and external validity. Nevertheless, a complete framework remains an important point of reference.

A relatively new concern in modelling are the dynamics of decision making (Tavasszy, 2020). In policy and innovation circles, response times in the transport system are increasingly recognized as becoming more important. Consider climate change, for example: most policies include a target year for achieving a desired effect (e.g. 55% emission reduction by 2030). The dynamics of decision making inside the system will determine how quickly the system will respond and whether climate mitigation targets can be met in time. Simulation models allow these dynamics to be included, but unfortunately there is still little empirical knowledge about the responsiveness of parts of the urban freight system. Strategic decisions will only be taken a limited number of times during the lifetime of a company, whereas the tactical investment decisions have a very long turnaround (years to decades) due to their capital intensity. Operational decisions may reveal stronger dynamics, but some decisions – like modes of transport and product packaging – may have a very long review frequency. The aggregation of many decisions may also lead to long system response times, even if many decisions are taken relatively quickly. When the total response time of the system on a policy is important, and key decisions are taken slowly, insight into dynamics is of critical importance to assess the feasibility and usefulness of policies.

Ultimately, researchers and practitioners have developed a practice of thinking about aggregate structures by partitioning the entire network of logistics decisions into larger blocks, that are relatively easy to model. Of course, the drawback of this is that information about detailed decisions is lost, that response mechanisms are not modelled completely or truthfully and that they may even provide misleading information. But, given the unsurmountable constraints of data availability and with the help of rigorous statistical validation, the method of aggregation has allowed science to progress.

As a basic conceptual model of the freight system, we find representations at different levels of aggregation. A crude one is the division into four key structures (Rodrigue, 2019): production structures, distribution structures, supply structures and transport structures. Herein, one faintly recognizes the traditional, passenger-transport-oriented approach of the four-step model – where distribution structures are irrelevant and transport structures are modelled with mode and route choice. From this starting point in the 1970s, increasingly sophisticated conceptual frameworks have evolved for freight transport. In a stepwise fashion, more and more logistical detail was added to the four-step framework for the purpose of improving predictive freight flows models – this included the explicit consideration of distribution structures, the inclusion of an agent-based view and the rooting of framework in multi-stakeholder ontologies.

The SMILE model (Tavasszy et al., 1998) recognized the difference between spatial flow structures for trade and those for transport. The former concern the inter-regional trade relations bridging producers and consumers (P/C relations (see De Jong & Ben Akiva, 2007)) and the latter concern the places where freight transport assignments mark their origin and destination (O/D relations (ibid.)). The two structures are bridged by distribution networks, where warehouses also act as origin or destination of freight movements. If one only wants to consider mode-specific O/D relations, intermodal transport networks also play a role, where transhipment centres will act as origin or destination. The SMILE model considered both interactions, also included a model of trade networks and was empirically implemented for the Netherlands. An urban freight model that appeared at the same time, which also modelled distribution centres explicitly, was GoodTRIP (Boerkamps & Van Binsbergen, 2000). This model had the same logic as part of SMILE but its empirical implementation was limited. Later, Roorda et al. (2010) presented the FREMIS model architecture that takes an explicit agent-based view, meaning that decisions of consumers and firms act as a starting point. The considered decisions differ from those of Riopel et al. (2005) in the detailed decisions and aggregates these into three types of artificial "contracts": commodity contracts, business contracts and logistic contracts. Prototype applications implementing parts of this framework were built for the Greater Toronto Area. Anand et al. (2014) considered dynamic interaction agent decisions explicitly in an agent-based model implementation for the city of Rotterdam, the Netherlands. Although the number of decisions considered is limited (sourcing, inventory, shipment size and routing), the conceptual framework of the model had a unique feature in the sense that it was built on a generic ontology for city logistics, based on linguistic processing and knowledge mapping of verbal and written text material. As we will discuss later, the latest generation of urban freight models, like Mass-GT (De Bok et al., 2021), SimMobility Freight (Sakai et al., 2020) and POLARIS (Stinson et al., 2020), have adopted the same range of decision-making problems. In other words, they have mainly moved forward in the empirical implementation of this same architecture, by using microsimulation and new data sources.

Research on predictive transport models has still not addressed several decisions from the Riopel framework, including, in the transport spheres, (1) type of carrier, (2) degree of consolidation of flows (internal or external), (3) fleet composition or (4) vehicle load plans. In the wider set of operational decisions, this gap is even larger and includes (5) material handling, (6) product packaging, (7) inventory management and (8) warehousing. Tactical and strategic decisions are rarely modelled at firm level, if at all, with the exception of the actual transport and distribution networks. New research work could address the necessity and feasibility of including these decisions in operational modelling frameworks.

In summary, Table 3.1 displays the prevailing, commonly used structuring of logistics decisions, with the most popular quantitative models used to portray these structures (partially or completely) in the right-hand column.

For each structure and model type, several studies have appeared, many in an urban context, producing empirically validated models for different regions in the world, from urban to global level (see Tavasszy et al., 2020 for further elaboration on these cases). The modelling methodologies applied have evolved gradually from zone-based models in the 1970s to agent-based approaches nowadays, where the latest models simulate the actions of individual firms. We note that these are not yet the individual decision makers, who would be consumers or responsible managers, but actions of abstract firms which assume specific sequence and speed of decisions as output from the firm as a whole. In the next section, we explore this evolution further and review the development of urban freight modelling approaches through time.

Evolution of Urban Freight Modelling Methodologies

Over the past decades, urban freight transport models have improved in their representation of logistics agent behaviour and spatial resolution and have become more accurate at addressing the complexities of today. We refer readers interested in general reviews of freight transport models to the most recent overview of de Jong, de Bok and Thoen (2021). We can discern three generations of models as they have evolved from the first iterations in the 1980s: aggregate, disaggregate and microsimulation models. They can be best characterized by the level of detail of their inputs and outputs, where disaggregate data refers to firm or shipment level, and aggregate data to the level of traffic analysis zones or geographical regions (Figure 3.2).

The first generation of models was built on aggregate data, largely by analogy to the four-step models in passenger transport, with aggregate choice models or zone-level empirical models like the direct demand models and gravity models. The second generation used disaggregate data and started to represent logistics process like trip chaining and physical distribution. The models were still applied at the zonal level. The third generation of models has taken the step to simulate actions at the individual agent level, which allows for an explicit model of connected logistics decisions but makes empirical validation more challenging. The focus of all these models has still been to produce information about yearly flows of goods. A next generation of models needs the disaggregate/disaggregate form as a basis to go in more depth in terms of showing operational details and shorter-cycled changes in the system. Table 3.2 summarizes these characteristics. We describe these generations in more detail below.

First Generation: Aggregate Approaches

The first series of freight transport models are founded on classic theories of economic activity and transport costs, formulated for aggregate agents: an average firm that represents all firms in one region (or, more generally, spatial unit of analysis or zone). Despite the obvious risk of aggregation bias, the zone based approach is an effective and proven method to simulate how a population of firms behave on aggregate. As the mathematical form is light and broadly known, operational models are quickly estimated and easy to validate and interpret. Contemporary models still carry the fundamental step-wise DNA of these models: transport costs affect decisions as to where to source products, how to choose the efficient mode of transport or how to route shipments. The scope of these models can be continental, national or regional. Data to develop these models (aggregate national or regional trade or transport statistics) have been around for decades, and sometimes are even available in time series. Most freight policy scenarios worldwide have been based on this type of model. Practical cases are numerous and include most, if not all, large-scale freight models, like the European Transtools I and II (Hansen & Rich, 2011) and the current national freight model BasGoed for the Netherlands (de Jong et al., 2011). Furthermore, the national freight model SMILE (Tavasszy et al., 1998) can be classified here. Although it used firm and shipment data to simulate freight movements, the estimated behavioural models were aggregate in nature.

For the reasons sketched above, this generation of models still forms the cornerstone of freight policy analysis. For that reason, it is important to continue scientific work to improve their validity. Recent streams of research work attempt to tackle the following challenges:

- Extending functional properties of models to model the effect of changes in distribution channels or intermodal transport chains (see, e.g. de Bok et al., 2018).
- Understanding and extending limits of validity. When aggregate models hide complex underlying behavioural patterns that are relevant for policy, these errors need to be understood and may give rise to model improvements (see e.g. Holguín-Veras et al., 2011).
- Representing heterogeneity of populations. Instead of assuming a non-existing average firm or commodity in the system, segmenting models or refining assumptions about underlying distributions can improve validity (see e.g. Marcucci & Gatta, 2014; Piendl et al., 2019).
- Modelling response sensitivity or response dynamics in the system. System dynamics models, time series regression models or econometric modes can provide new policy-relevant insights (see e.g. Ferrari (2014) or Davydenko et al., 2021).

Second Generation: Modelling Logistics Behaviour with Firm- or Shipment-Level Data

With a second-generation model, we distinguish approaches that have more detail concerning logistic behaviour, including lower-level decisions, decision-maker preferences and interactions between decisions. In these models, several layers of logistics network modelling were added to the freight demand models.

The focus of these models is on simulation of firm behaviour at the zonal level, taking into consideration constraints such as location and availability to transfer goods between modes in multimodal transport chains or multitier distribution structures. The methodologies applied in these models represent advances in understanding of logistics processes, new techniques in discrete choice modelling and increased use of detailed data. Theoretically, connections are made between flow models and random utility-based discrete choice models, transforming the formulation from physical flow models using aggregate agents (spatial zones) to choice models for disaggregate agents (decision makers or firms). The attractiveness of these models is their behavioural validity at the firm or shipment level.

In addition to national or regional statistics, these models especially build on micro-level (firm- or shipment-level) information from commodity flow surveys, freight trip diaries or establishment surveys. Due to their high costs, large-scale shipper surveys or commodity flow surveys are only available in a handful of countries (US, France, Sweden, Norway, Japan). This has resulted in a limited number of applications.

As with the first-generation models, the application of second-generation models has remained mainly at a zonal level, combining aggregate and disaggregate approaches to link zonal flow models to firm-level behavioural models. Where surveys include stated preference interviews, special care must be taken to calibrate models to real-world flows, which often involves tuning a model to aggregate statistics.

Representatives of this generation of models include the ADA models in Scandinavia (De Jong and Ben Akiva, 2007), TransTools III (Jensen et al., 2019), TriMode (Williams et al., 2017) and the Strategic Freight Model for Flanders (Grebe et al., 2016).

This stream of modelling is uniquely suited to explore decision making in the logistics sector. In principle, every one of the 48 logistics decisions lends itself to studying the alternatives in their unique context, the decision processes, objectives and preferences of actors. As decisions can be recorded at the individual level, this is a fruitful area of study. Although traditionally (as in the abovementioned models) the emphasis has been on multimodal routing choices, in recent times, the emphasis has been on understanding departure-time choice, ordering behaviour (see e.g. Chapter 4 by Comi and Delle Site), firm-level freight trip generation (see Chapter 6 by Sánchez-Díaz and Castrellon-Torres) and distribution choices (see Chapter 5 by Sakai et al.).

Third Generation: Microscopic Simulation

The second generation of freight models showed that valid disaggregate choice models are feasible. From here, the next step was to explicitly represent the agents and their decisions instead of aggregating the results to zonal level. In this third generation, we use the microscopic simulation approaches. The scope of these models is large-scale simulation of freight demand for all agents in a study area. Models simulate how all firms behave individually, taking into account the preferences and constraints of these agents explicitly.

Typically these models take a step down in aggregation level, not just for their estimation, but also for their application: individual actors are modelled explicitly and their behaviour is included in the output of the model. Also, dynamics portrayed become explicit, adding detail to the typical yearly flows of the previous generations by using an event-based approach. In addition, these models are also shipment based: the logistic decision making explicitly represents the units of transport in order to better model the decision behaviour around consolidation of goods transport. This stream of models implied a deeper representation of logistic behaviour across networks and freight service layers, and the simulation of vehicle patterns and routing. Theories typically used include discrete choice models and Monte Carlo simulation or microsimulation of network usage. Dynamic agent-based models also fall within this category: they are a novel approach incorporating learning and emerging behaviour into the simulation. The combination of discrete-choice models, based on stated preference data, and agent-based models within an integrated modelling framework can be fruitfully adopted to *ex-ante* assess stakeholders' policy acceptability accounting for heterogeneity and interaction effects (Le Pira et al., 2017).

The recent microsimulation implementations of freight transport demand models often take advantage of increasing automation in data collection, providing more detailed, extensive or dense transport surveys. Types of data collection include logistic data on freight demand (establishment survey) or freight transport (trip travel diaries). Often data sets are extended with other combinations of automated data collection (GPS, roadside camera registration) or available geographic information about the location of activities (Yang et al., 2022; Mohammed et al, 2023). The microsimulation approaches operate with more spatial detail, and are designed to fit better with the urban context in the transport domain. The models are used to explore city logistics developments or evaluate policies at this level. Recent examples of operational microsimulation models include ULLTRA-SIM (Sakai et al., 2019), Simmobility Freight (Sakai et al., 2020), MASS-GT (De Bok et al., 2021), POLARIS (Stinson et al., 2020) and MATSim (Bean & Joubert, 2021).

Fourth Generation: Living Labs and Digital Twins as a New Context

All the above models are designed to support policy making, rather than private strategy building or management. This implies that the models are part of very slow and long decision cycles: infrastructural and regulatory policies that take years to decide, to implement and to take effect. In future generations of models, we expect the main paradigm change to lie in this area: a change of focus towards support to much shorter decision cycles. We see two stages of shortening decision cycles. The first involves decision making by multiple stakeholders around collaborative innovations in city logistics (see also Chapter 16 by Le Pira et al.). Through experimentation in living labs, public and private partners co-create changes in the urban freight landscape. The second stage builds on new opportunities in sensing and information processing, allowing urban management to include city logistics. This operational-level decision making in smart cities relies on quick estimates of expected effects, currently built around urban management dashboards, but with a full digital twin for the city as ultimate vision for the future. The heart of a digital twin is a model of the city, including its behaviour, for example Lim et al. (2019) or Marcucci et al. (2020). Below, we further develop our ideas for this next generation of urban freight models.

Changing Requirements and New Directions for Modelling

As introduced above, the urban freight context is changing in many directions for various reasons. Consumption is slowly becoming mass individualized, implying smaller and more frequent shipments with high service levels. Consumers have become important generators of freight movements due to e-commerce returns, consumer-to-consumer shipments (e.g. pre-owned products) and return of used products and materials. In response, stakeholders are extending their business by collaboration and changing business models, working on relatively complicated innovations (e.g. crowdshipping, city hubs, collaborative schemes, the physical internet). This creates a strong evolution in business models, such as with firms deciding to take on roles which fall outside their original boundaries. For example, carriers may take on forwarding services and e-commerce sales platforms may incorporate physical delivery, crowdshipping or financial services. Figure 3.3 shows how different agents in a city can take on multiple, competing as well as complementary roles. In this specific case, final delivery is taken over from the courier by the urban consolidation centre operator while the courier assumes the role of logistics service provider and network coordinator.

Models can also be used to explore new solutions, such as real-time bay reservation and monitoring (Comi et al., 2018), which require the use of telematic tools. The increasing complexity of logistics business models affects all private and public stakeholders, not just in relation to markets of logistics services but also in transport equipment, information technology and real estate. Many new questions arise concerning the role of public authorities to regulate service markets, and the position of private companies in collaborative networks (Zenezini et al., 2018). In contrast to earlier government-induced city logistics measures, which are sometimes taken on without regard for sustainable business models and therefore fail (Allen et al., 2007) stakeholders now engage in collaborative processes to identify shared values, break down Big-Bang innovations into smaller steps and create consensus on the feasibility of innovations before investing. The close involvement of all stakeholders proves to be critical for achieving a sustainable state of the new system. This *living lab* approach is slowly becoming standard practice in multistakeholder city logistics innovation (Quak et al., 2016; Gatta et al., 2017; Fredriksson et al., 2021). A more detailed contemporary overview of this approach is provided in Chapter 17 by Quak and Nesterova. For simulation models to be relevant to facilitate the evolution of these new concepts and business models in urban freight transport, these models need to represent these stakeholders and the diversity in urban freight demand.

Living Labs and Digital Twins: Requirements

Living labs and digital twins, characterized by behavioural and simulation models, play an important role in supporting participated planning processes, where reactions to structural change and policy measure implementations are investigated (Marcucci et al., 2020). To facilitate the living lab movement, cities are becoming increasingly smart, shortening their own decision cycles to experiment with temporary changes in regulations and new approaches to urban traffic management. Urban freight models can support this development. The model requirements differ considerably from those in policy evaluations, however:

- Experimentation cycles in city logistics living labs are shorter than the conventional policy-making cycles (months instead of years); models will have to be set up quickly for cities and provide answers within days or weeks.
- As industry wants to understand effects on operations, the models need to include a description of agent- (firm- or establishment-) level

impacts of innovations, including shorter (operations) and longer-term (market position) effects.

- In order to simulate logistics processes consistently, the models need to have a representation of freight shipments. Conventional vehicle-based models fall short in adequately simulating impacts of consolidation or cooperation between stakeholders on shipment patterns.
- Models are used as predictive dashboards towards a larger stakeholder community and will need to be comprehensive in terms of the relevant agents and impacts accounted for. Also, they will require acceptance by all involved.

A subsequent development which requires even more detail and speed in models involves urban management. Cities are leaning more and more towards the use of real-time information about the state of their systems to optimize the use of urban space by access control and pricing, and to mitigate negative impacts with traffic control. These operational, control room functions require models that can provide even shorter-term forecasts of user behaviour at a lower, agent-specific level of detail. Here, urban freight models become part of a new context of the smart city movement and are developing towards digital twins of cities (Farsi et al., 2020).

The fast digitalization of the sector, with rapidly increasing data availability, supports this change (Bukrinskaya & Dyukova, 2019). Numerous sensors allow immediate tracking of freight shipments, freight traffic and its impacts. New information that is becoming widely available in digital form includes historical records and streaming data concerning logistics services (planned and executed tours and trips, service times, stops, etc.); cargo (e.g. digital bill of lading, cargo appearance, etc.); vehicles (position and driving conditions, driver behaviour, etc.), traffic (intensity, safety, compliance, etc.) and the environment (pollution, weather, etc.). As the amount of data available is abundant and operational in nature, it is useful for dynamically adaptive decision making. Most of these data, however, provide partial information and it remains a challenge to smartly combine and link different sources of data, whether they are static statistics or dynamic operational data. Eventually, it is also conceivable that urban management decisions are automated on the basis of these predictions in a model-based, predictive control cycle. As these decisions in urban management are short cycled, this application requires even faster analysis which is accurate for a wide variety of situations. Here, artificial intelligence will be used more and more to tune models and their predictions to observed reality, and modelling will become increasingly data driven.

Research Directions

Short-term research directions deal with a successful application of these new sources of information into simulation models for urban freight transport to support strategic policy making. The increasing data availability and changing use of urban freight models call for guidelines to develop empirical descriptive urban freight models. The third generation of microsimulation models simulates individual agents and interdependent logistic decision making: new data allow the development of these models, but require a comprehensive architecture and smart intelligent procedures to combine and link different sources of data. The complexity of these models requires a smart development procedure that differs from the conventional theory-driven approach. Similar to software development or complex product design, a minimum viable product (MVP) principle can be adopted to follow an evolutionary approach. In this approach, the urban freight model starts with a simple descriptive and data-driven baseline model with as little choice modelling as possible, and, in a stepwise process, complexity is added. These additional steps can include the implementation of a choice model for tour formation, or delivery time modelling, or the further segmentation of logistics agents. This approach was also adopted in the development of the MASS-GT model (De Bok & Tavasszy, 2018). Each intermediate version of the model allows learning about the model design and cases in city logistics.

Subsequently, as a longer-term research and development direction, models will have to evolve by gaining experience in innovation processes and by functioning within an urban management context. This evolution will include the following capabilities:

- Applicability within multistakeholder living labs around innovation themes such as (1) horizontal and vertical integration of services as well as (2) changes in fiscal arrangements from government and regulations for use of urban space.
- Adoption of multistakeholder frameworks for modelling including dynamic business models and a linkage to performance measurement using industry data.
- Process-wise, these models will need to be embedded in city logistics living labs, both technologically and socially.

- Ability to function in a fast-paced, model-based predictive control cycle, allowing sensing of performance of cities, prediction of expected future states, calculation of optimal control measures and actuation of measures for urban management.
- Ability to optimize across different objectives of different actors, suggesting or prescribing a promising course of action. This will require a merger with optimization-focused models of freight distribution (see, for example, Rezaei et al. (2020) and Kim et al. (2021) for two examples in a physical internet context).

The above directions of research will together shape the development of the fourth generation of urban freight models.

Conclusions

In this chapter, we have summarized the past and current developments in urban freight modelling. We have also presented a vision for future development.

Over the past decades, models have undergone a development which has entailed increasing use of disaggregate data and a recognition of the main logistics decisions by which firms respond to changes in the environment, policy induced or otherwise. The latest generation of models is characterized by the use of microsimulation aiming to reproduce tactical and operational logistics processes. The user environment of models is predominantly one of long-term policy making, where models inform policy makers about possible long-term futures of the city under different policy scenarios. Nowadays we are seeing more collaborative policy making coupled, where public and private decision makers create new decision-making arenas and innovation processes.

In this changing context, we have sketched an evolutionary path of freight modelling which revolves around two lines of development:

1. An increasing sophistication in the description of behaviour of logistics agents, by explicit modelling of decisions at the individual firm level and at the level of supply chains. This requires the modelling of more decisions than before based on disaggregate data related to logistics operations, and creates increased external validity of models.

2. From a policy perspective, the increased joint use of models by multiple stakeholders as digital twins in a living lab context. This requires closing of the sensing-actuation loop by direct linkages to streaming data about logistics processes, and produces new model outputs which related directly to decision processes of stakeholders. Models are increasingly data driven.

The above two developments converge in the notion of models as digital twins of urban freight systems. They are built on the principles of event- or agent-based simulation, work at a detailed spatial resolution and are integrated in an urban management control cycle. They are transparent towards both public and private stakeholders and create a strong sense of face validity with these actors. They allow a fast processing of large volumes of incoming data and can suggest promising courses of action to managers. This specification of decision support for urban freight systems brings many challenges – it will require social scientists, engineers and computer scientists, to work more closely together than ever before.

Appendix 3.1: Logistics Decisions (Riopel & Langevin, 2005)

Strategic Planning Level

1. Definition of customer service
2. Customer service objectives
3. Degree of vertical integration and outsourcing

Physical Facility (PF) Network

4. PF network strategy
5. PF network design

Communication and Information (C&I) Network

6. C&I network strategy

Inventory Management

7. C&I network design

Demand Forecasting

8. Forecasts of demand magnitude, timing and locations
9. Inventory management strategy
10. Relative importance of inventory
11. Control methods
12. Desired inventory level
13. Safety stock

Production

14. Product routing
15. Facilities layout
16. Master production schedule
17. Production scheduling

Procurement and Supply Management

18. Procurement type
19. Specifications of goods procured
20. Suppliers
21. Order intervals and quantities
22. Quality control

Transport

23. Transport modes
24. Types of carriers
25. Carriers
26. Degree of consolidation
27. Transport fleet mix
28. Assignment of customers to vehicles
29. Vehicle routing and scheduling
30. Vehicle load plans

Product Packaging

31. Level of protection needed
32. Information to be provided with the product
33. Information media
34. Type of packaging
35. Packaging design

Material Handling

36. Unit loads
37. Types of material handling equipment
38. Material handling fleet mix
39. Material handling fleet control

Warehousing

40. Warehousing mission and functions
41. Warehouse layout
42. Stock location
43. Receiving/shipping dock design
44. Safety systems

Order Processing

45. Order entry procedures
46. Order transmission means
47. Order picking procedures
48. Order follow-up procedures

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Figure 3.1 Network of logistics decisions surrounding the transport function (see Appendix 3.1 for reference numbers) *Source:* Riopel and Langevin (2005)

Figure 3.2 Three generations of freight models *Note:* A = aggregate; D = disaggregate

Figure 3.3 Blurring of business model boundaries in collaborative city logistics *Source:* Zenezini et al. (2018)

Table 3.1 Framework of logistics structures and models

Logistics sub-structure	Model ype
Production structures or intersectoral trade	Production and consumption functions (CGE) models, Input/output models, Freight (trip) generation
Spatial supply structures (firm level) or trade relations (aggregate)	Supplier choice models (firm level) Gravity model (aggregate)
Distribution structures or channels	Distribution structure models Shipment size and frequency models
Transport structures	Carrier (type) choice, Mode and/or route choices Vehicle type choice Detailed routing and scheduling models

Table 3.2 Evolution of urban freight model systems

Generation	Agent level of underlying theory	Spatial resolution of outputs	Time resolution of decisions	Time resolution of output	Type of application
1 (1970–)	Aggregate	Zone	Year-on-year	Yearly performance	Public policy
2 (2000–)	Disaggregate				
3 (2010–)		Zone + Firm	Event-based		
4 (Future)		Place + Agent		Week/month	Public + private co-innovation