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COMPUTING TECHNOLOGY AND ITS APPLICATIONS IN URBAN LOGISTICS

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Introduction

Urban logistics is growing in complexity. While consumers still buy the majority of their goods in brick-and-mortar retail outlets, online shopping is becoming more and more popular. E-commerce allows consumers to order at home and choose between many delivery options. Automated logistics management systems assist in the planning and execution of deliveries, with sophisticated online marketing and service systems that instantly adapt to changing customer needs. These e-commerce platforms process large amounts of data and have an increasing degree of autonomy in logistics decision-making, be it about which products are sold to whom or which way they are shipped. All this data also allows improved strategic intelligence for business and government, to make decisions about operations, investments and even public policies. As the pressure on urban logistics is increasing to become environmentally friendly and socially equitable, new management approaches are needed to cope with the burgeoning of platforms and continuous launching of new online services. Companies apply data analytics to develop consumer profiles and calibrate their omni-channel service offerings to their customers' needs. By leveraging rich data sources about citizen and business activities, city governments are also increasingly capable of recognising problems and quickly responding to them through new regulation. Digitalisation has not only created new ways to earn money, but it has also empowered politicians and their constituents, the citizens, to act in informed ways. In short, computing technology and its applications are revolutionising urban logistics.

Interestingly, digitalisation and automation have been developing since the 1960s, it seems that only since the turn of the century, after the mass deployment of internet connections and the smartphone, the digital industry has tapped into the vast resource of consumer needs and powers. Still, however, in many ways, the digitalised world of logistics is old-fashioned. Most private and public computer systems are centralised, many global logistics standards are not harmonised or adjust badly to changing practices, most of the data exchanged is paper-based, and the service industry is still fragmented. As part of the digitalisation revolution, these practices still have to change. When they have, data will flow even more easily and larger systems can be coordinated or optimised, creating another step change in efficiency and effectiveness of logistics systems.

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Figure 16.1 Conceptual framework for this chapter

The aim of this chapter is to systematically explore this development, by means of an inventory of relevant computing technologies and an analysis of their role in urban logistics, and provide an evaluation of their expected impacts. The conceptual model above is followed, which builds from individual computing technologies, to purpose-built logistics innovations, to future urban logistics systems into which these innovations converge (Figure 16.1).

The chapter is built up along these lines. The following section briefly introduces the main innovations in computing technology that affect logistics systems. This is followed by an exploration of how these technologies individually or collectively seep into system innovations, creating increased logistics value. An identification of the three concurrent development pathways for future urban freight systems, that build on these innovations is provided and finally, the chapter is summarised and closed in the conclusions.

Innovations in Computing Technology

Without the ambition to give a comprehensive account of the new opportunities of the ICT revolution, this section reiterates the main technological innovations that have found application in urban logistics, or which are being considered. Recent reviews (Büyüközkan and Göçer, 2018; Ferrari et al, 2022, Iddris, 2018) have detailed these technologies and discussed their generic impact on logistics systems. Four broad areas of innovation are distinguished in which computing technology developments can be characterised: hardware, software, data and networked applications.

Ubiquitous hardware: Following a continued trend of decades, computers are becoming smaller and more powerful, to an extent that they will be less obtrusive making them portable and wearable, integrated into everyday apparel and clothing. Satellites and embedded software allow all-to-all communication between objects. After the smartphone and smartwatch, tracking of objects and sensing of their states at low prices, and virtual and augmented reality gear are the next practical steps.

Big data storage and processing: The digitalisation of administrative systems is now moving from the early stages of governmental spheres, to single and multi-company proprietary systems. In places where these spheres meet (e.g. digital bills of lading) that innovations in logistics affect entire communities. It also allows an increase in data availability within these communities, and automation of data processing facilities, eventually including automated decision-making. The development raises new concerns about data ownership, exchange and use. Not only are new data markets developing but also the governance of these markets is in its early stages.

Decision support software: The increased availability of data, especially of streaming data from operational processes has opened new possibilities for data analytics. The data analytics pipeline includes capture, processing, storage, analysis and usage of data for various purposes, including monitoring and evaluation of processes, diagnosis of problems, prediction of activities and predictive purposes, to optimise and manage processes. Our ability to reproduce the working of a system with software has strongly improved, leading to the advent of digital twins of systems. Eventually, decision support software could evolve into automated decision-making, where humans are no longer critical. This move towards artificial intelligence (AI)-based operations is problematic where demands on explainability (Taj and Zaman, 2022) are high, or moral decisions are at stake. Current applications of AI are still modest, therefore, focusing on pattern recognition from data to ease interpretation of large amounts of data.

Networked applications: The miniaturisation of electronics has spurred the development of decentralised and distributed (cloud and fog) computing, where computing power is shared and divided amongst different objects. If these objects happen to be parcels or containers, shipments are ready to become intelligent, opening the door towards completely decentralised decision-making in logistics. It requires distributed software, supported by IoT (internet of things) connectivity and new platform technologies to aggregate signals, for such distributed systems to work. Platform-based markets that connect supply and demand for services and collaborative, or cross-chain control towers are concrete examples.

Collective impact: One can look at individual technologies, but also at how these work together to create new opportunities to manage the urban freight transport system, and how they cooperate with humans. This idea of technology convergence or human-machine convergence is important in studies of the future of larger social-technological systems. Futuristic visions that include notions of convergence and are relevant for urban logistics include Cyber-Physical Systems (also called Industry 4.0) and the Physical Internet. We argue that it is important to take such visions as a starting point. Not only does it help to sketch a realistic image of how technologies would be co-existing, but it also allows us to see their roles and functions in the system, and the way in which together they determine the future performance of the system. Such new configurations of new technologies are capable of forming entirely new services (e.g. e-commerce through a smart combination of digital trading, logistics and banking) or opportunities to control the urban logistics system in different, more productive ways than before (e.g. smart cities through digital twins and control towers). Tang and Veelenturf (2019) even argue that logistics has a strategic role in the Industry 4.0 era and that, together, these technologies and services can also create environmental and social value. In the following section, three different ways are discussed in which these technologies together can create new added value in the logistics services sector.

Impact Pathways of Computing Technology into Logistics Systems

The expected benefits of digitalisation of logistics systems are enormous. The World Economic Forum estimates that improved coordination will provide 3.4 trillion USD in new business value for the logistics services industry, which is in the order of magnitude of 10% of the current logistics services market (Snabe and Weinelt, 2016). But how will this new business value materialise? This section first looks at the principles of value creation from digitalisation, compared to a formerly physical world. The promising innovative implementations in urban logistics are discussed both it in existing services and in new ones.

Value creation by digitalisation involves a marriage between physical and digital systems, in a way that new customer value is generated. Hofmann and Ruesch (2017) provide an introduction to the way in which digital technologies can add value to logistics systems. Their conceptual model is used as inspiration and a simplified version of this is taken as a starting point (Figure 16.2).

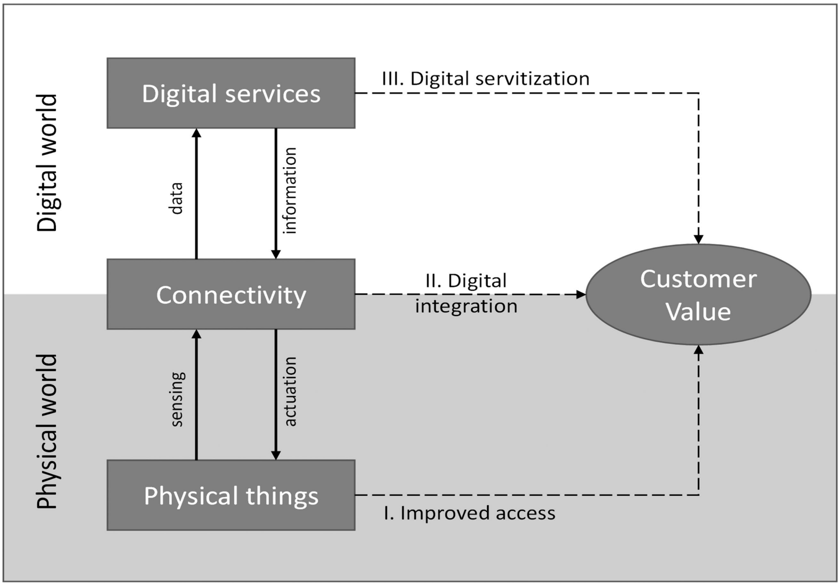

Figure 16.2 New business value of physical-digital integration in logistics

The Figure shows that there is a physical world (lower half of the figure) to which the new digital world (upper half) is adding value, by improving access, providing additional services or reducing physical needs with digital services. The interface between the two worlds is arranged through a connectivity layer, exchanging data and information and physically connecting them via sensors and actuators. Sensors include traffic detectors in roads, cameras and air monitoring devices. Actuation in the physical world happens through logistics management decisions of humans and their decision support systems but also of automated control devices. One can distinguish different management decisions here, for different actors and time cycles. For example, the classical infrastructure policy loop is a long-term, public management cycle, responding to the reporting of accessibility problems, suggestions for solutions, votes in governmental arenas and policy implementation – altogether, it can take decades before an infrastructure policy cycle is completed. Shorter time cycles involve investment decisions in real estate and fleets by service providers, of changes in transport service offerings, of daily planning of delivery trips and their execution, with drivers making decisions by the minute, and traffic lights responding within seconds. It is widely expected that these decisions will benefit from digitalisation.

Indeed, the addition and completion of a layer of digitalised services (the "digital world" in Figure 16.2) will allow these decisions to respond more quickly, accurately and comprehensively to information from sensors. They will be quicker, as digital information doesn't rely on paper-based exchange through multiple layers of organisations. They will be more accurate as data are recorded digitally, allowing them to be shared, improved and analysed easily, so that evidence-based decision-making becomes easier. Also, they will be comprehensive as lower costs of communication mean that decisions can be coordinated to be consistent and mutually reinforcing. Altogether, digitalisation is expected to increase the customer value of all existing services in the physical logistics world. In terms of customer value, this means an increased value of the availability of goods.

In addition to this new value of availability, a new series of digitalised services will develop and, with these, new physical services will emerge that can only exist with digital support – these are shown as value of digital servitisation and value of digital integration as shown in Figure 16.2. New digital services can be manifold. The simplest form of service is the digital delivery of previously paper-based information (e.g. a digital invoice, customs declarations); here services have become digital, and physical services have become replaced or enhanced by digital services – servitisation. New information during the shipping process will become available, like status information or delivery time predictions. Also, digital information upstream (from consumer to service provider) will be possible, allowing changes in delivery when needed. This can invoke a delay or acceleration of shipments or even a transfer of ownership, if re-routing, temporary storage or return arrangements are made. Finally, also completely new forms of physical delivery (e.g. crowd-shipping or instant delivery) will become possible, which can only exist when all information systems are digitalised and new digital platforms are created allowing fast access and communications. This servitisation is exemplified by the growth of the platform economy, where the ICT sector also competes with incumbent, less digitalised logistics services through digital integration services (see Müller and Knitschky, 2021).

Table 16.1 lists the most frequently named digitalised innovations in urban logistics. Each innovation includes a brief description and is classified according to (1) the leading technology as discussed in the previous section (hardware, data, software or networked applications) and (2) the type of service improvement: value in (physical) availability of goods, value in digital servitisation and value in digital integration.

The above-listed technologies are not independent. They can interact in the transport chain (e.g. lockers and autonomous delivery vehicles) causing complications in the delivery of goods. They can depend on each other or reinforce each other (e.g. RFID and transport process information) and could even compete (e.g. IoT and platforms). These interdependencies are important to understand and manage, as they determine the speed at which technologies are adopted and, eventually, the speed at which their joint deployment can create synergies to realise the expected total benefits for the logistics system. This joint deployment is the subject of the next section. Our focus will be on the long-term vision concerning this convergent use of technologies. The section does not detail short-term interdependencies and interconnections between technologies (e.g. TMS and WMS integration issues). Nor does it attempt to predict whether or when individual technologies will see a breakthrough (e.g. blockchain applications). Instead, the question addressed is by which logic these technologies are likely to converge in the urban system: what will drive their joint deployment, what will be their expected collective impact, and how can one describe the resulting strategic change at the level of the urban logistics system? The following discusses three ways in which individual technologies are converging into the urban logistics systems of the future.

Convergence into the Urban Logistics System: 3 Pathways

To understand the future functioning of applications of computing technologies, in relation to each other and within the entire system, they are positioned in light of the vision of the Physical Internet (Montreuil, 2011). The Physical Internet (PI) is a long-term vision for the global logistics system where due to far-reaching digitalisation and automation of all processes, physical distribution systems around the world can be optimised across large, multi-company networks. This optimisation affects all decisions in logistics, from daily routing, vehicle and mode choice, to distribution and even ownership of goods. The current

Table 16.1 Digitalised innovations in urban logistics

Innovation	*Key proposition*	*Typical application*	*Key tech (H/D/S/N)*[a]	*Value (A/S/I)*[b]
Drones	Fast access to goods for difficult (built/remote) areas	Urgent and rescue logistics	S	A
Robotized warehouses	High capacity, flexible handling and sorting	Complex cross-docking and warehouse ops	H/S	A
Blockchain	Access to a distributed transaction ledger	Smart contracts	D	S
Product and service sales platforms	Shop from home, service optimisation	E-commerce websites, crowd logistics, collaboration, auctions	N	A S
Advanced data analytics	Insights and predictions from big data	Forecasting, business intelligence (BI)	D	I
Electric vehicles	Environment-friendly delivery	Zero-emission zones	H	S
Autonomous vehicles	Lower transport costs, DIY (un)load	Niches (humanitary, restaurants)	S	S
Coded parcel lockers	Flexibility in pick-up and delivery	Alternative for home delivery	S	A
Barcodes and RFID	Information embedded in shipment	Supply chain digitalisation	H	I
VR/AR applications	Personal and situational information	Shopping experience, warehousing	H	S (consumer) I (services)
Transport and shipment process information	Track- and traceability, forecasting	Communication within supply and transport chain	D	S (consumer) I (services)
Digital twins of hubs, chains, cities	Enhanced business intelligence (BI), control and autonomy	Niches (military, production)	S	S (BI) I (control)
Internet of Things	Objects exchange information autonomously	Wearable tech, object tracking, inventory management	H	I
3D printing (additive manufacturing)	Production of objects at home, customizability	Specialised small products (niches)	H	A S

a Hardware, data, software or networked applications
b Value in (physical) availability of goods, servitisation and integration

roadmaps for the Physical Internet to be completed reach until the 2040s (ALICE, 2020) while experts believe that this timeline is too short (Fahim et al., 2021). While, over the course of a decade, an extensive body of literature has developed about the PI, the topic of urban logistics has not been treated in much detail. Based on the limited literature that operationalises the PI for urban logistics, i.e. hyperconnected urban logistics (e.g. the conceptual and quantitative models in (Crainic and Montreuil, 2016) and (Kim et al., 2021) respectively, there is no reason to believe that ICT will be deployed in a different way in urban logistics than in the wider, global system. This chapter develops this reasoning for deployment of specific technologies and of their convergence, into the PI system.

In the context of urban logistics, an important and underdeveloped part of the PI literature, is its governance. While the PI roadmaps do mention that the PI needs some form of public governance, this need has not been operationalised in much detail. At least two characteristics of the PI make it necessary to pay special attention to its governance in an urban freight setting. Firstly, the main promise of the PI vision is the expected quantum leap in logistics efficiency and effectiveness. Although this probably will have significant impacts on emissions and safety risks of the system, these impacts remain externalities, meaning that incentives for their containment are not built-in. Secondly, the PI will be optimised at the system level, meaning that there will be distributive effects, concerning both the internal, logistic KPIs as well as the external impacts. As, also here, the basic definition of the system lacks incentives to steer the distribution of effects (and rather steer on optimising the aggregate), one cannot tell beforehand whether the resulting distribution will be socially acceptable. Therefore, some form of control mechanism must be developed that keeps the PI in the urban area within bounds, supported by the same advanced levels of ICT.

Instrumental for both developments above will be decision support tooling. Although one can expect that many decisions at a tactical or operational level (such as dynamic planning of shipments) will be automated, especially strategic or long-term decisions (such as investments in innovations) will be human-driven and subject to a process of alignment between public and private stakeholders. New computing technologies also provide important opportunities to support these alignment and decision-making processes. Although digital twins are already mentioned in Table 16.1 as one of the individual innovations, we argue that they are a convergent technology also, as more and more features of cities accumulate. Moreover, their development and use in the urban environment depend on the successful deployment of the other technologies. These are discussed in the last part of this section.

Pathway 1: The Physical Internet

Montreuil (2011) and subsequent work on the foundations of the Physical Internet (PI) defined a number of key building blocks for the PI:

- **Unified set of standard modular logistics containers, containerised logistics equipment and technology** promote the shared use of assets, reducing fixed costs and improving utilisation levels, while in the longer term also reducing the global pool of transportation assets. This standardisation is aided by **standard logistics services and operation protocols** which allows asset sharing through interoperability.
- **Certified open logistics facilities and open logistics service providers** allow to specify service offerings that are transparent towards a broad base of potential clients, support easy entry and exit of service providers and switching of clients between service providers.
- **Information systems** that include global logistics monitoring; smart data-driven analytics and logistics decisional and transactional platforms. Clearly automated and cross-system decision-making requires large-scale continuous information exchange. These systems should evolve to an extent that PI operations can be run reliably. Automated decision-making implies that sensing information, analytics and actuation (execution of decisions) can all function in very short timeframes (say, seconds).

Table 16.2 Role of advanced computing technology in the PI

Innovation	*Role in the PI*
Blockchain	Supports smart contracts and decentralised sensing of events
Product and service sales platforms	Digital entry for consumers to all PI services
Advanced data analytics	Allows AI-based real-time decision-making
Autonomous delivery vehicles	Strong reduction of transport costs
Coded parcel lockers	Allows sharing of locker space
Barcodes and RFID	Required for decentral data and automated processing
Transport and shipment information	Required for track- and traceability, forecasting, certification
Internet of Things	Allows distributed information carriage and sharing
Digital twins of hubs, chains, cities	Lower-level DTs can be embedded in a city DT
3D printing	Ultimate postponement of manufacturing

Several of these are dependent on step changes in our digital systems, while the last building block clearly shows the dependence of the PI on the establishment of a control loop, from monitoring to analytics to action. This could extend in several directions. Pan et al. (2017) add three requirements to this for these components to function as a self-organising system: openness, intelligence and decentralised control. This will eventually lead to a so-called "hyperconnected" transportation system, where all transportation options are possible, interoperable and available to choose the best alternative that the circumstances require. The degree to which such an advanced state of the freight logistics system can be achieved heavily depends on the availability and performance of computing technology. Table 16.2 sketches the role of the relevant computing technologies in the PI. Different technologies have different roles, while some are not indispensable within the PI vision. This underscores the idea that the PI is a convergent innovation for various computing technologies, as they will all work within the same system.

Pathway 2: Control in the Smart City

The focus of this section is on applications that oversee the functioning of the urban logistics system within its social and environmental context. Next, it also examines how computing technologies are converging into a control mechanism that keeps freight activities in the urban environment within acceptable limits.

Why is control necessary, and how is it exercised now? Despite its sheer necessity, urban freight transport also has adverse effects that cannot be repaired by private markets and justify government intervention. In order to protect their living environments, local and national governments are setting ambitious goals, such as halving the use of "conventionally-fuelled" vehicles in urban transport by 2030, and to phase them out in cities by 2050. Recently, the EU set a specific goal of achieving "essentially CO_2-free urban logistics" in major urban centres by 2030. The measures being taken can be summarised as *access management* and include low emission zones, time windows, axle-weight and/or length limitations. These practices are usually quite generic in their regulatory approach, and locally limited in their applicability. Applying the same regulations everywhere usually does not address specific challenges of specific cities nor does it always confront the relevant actors (e.g. heavy duty vehicles delivering to shops during the morning or the many "white vans"). The fragmented national landscapes of regulations cause difficulties to transport companies that operate in several cities as they have to cope with a variety of rules and regulations. Also, access management typically has static regulations, i.e. fixed in time, and cannot adjust to temporary changes in the state of a city. In short, the current system of fragmented and static access management can be counterproductive and even cause detours, illegal parking and unnecessary emissions (Quak, 2015).

Digital innovations in urban logistics services could potentially contribute to more tailored and intelligent access schemes for cities. Cities that use digitalised services accessible to all are now using the label *Smart City*; logistics systems can be a part of this concept. The potential for identification of vehicles and their location as well as communication with the urban environment enables new forms of access management and enforcement of regulations. Geofencing is a technology based on telematics and satellite positioning which allows to remotely monitor a geographic area surrounded by a virtual fence (geofence) and automatically to detect when tracked vehicles enter or exit these (urban) areas. Sensors are needed on the vehicles for communication with satellite systems delimiting specific urban zones. The long-term vision would be that each city is divided into geofenced zones and that is possible to change access requirements for specific urban freight vehicles to these zones in real time, adapting to the current needs of urban areas. Applied to logistics, this technology provides a possibility to enable intelligent access management for the specific zones, including an automated data collection and monitoring process, by means of:

- Dynamic regulation of pedestrian zones, low-/zero-emission zones;
- Parking, kerb-side loading/unloading;
- Use of public transport lanes;
- Dynamic time windows of deliveries;
- Use of digital permit systems including payment and auctioning;
- Monitoring of drivetrain use (e.g. in case of hybrid vehicle: electric or diesel);
- Digital enforcement of regulations;
- Communication between traffic lights and heavy vehicles to optimise traffic flow.

Table 16.3 shows the relevance of computing technologies for the Smart City. Clearly, one can see that transport data generation, analytics and communication are central in this proposition.

Table 16.3 Role of advanced computing technology in control of urban logistics in the city

Innovation	*Role in smart city control*
Blockchain	Allows distributed control of shared space
Product and service sales platforms	Allows auctioning of permits
Advanced data analytics	Insights and predictions from big data on city performance
Electric delivery vehicles	Locally environment-friendly delivery
Barcodes and RFID	Support geolocation and access control
Transport and shipment information	Support geolocation and access control
VR/AR applications	Improved visibility of processes and impacts
Digital twins of hubs, chains, cities	Improved visibility, control and autonomy

These applications all use the opportunities offered by advanced computing technology and can result in more evidence-based and fair policy measures in urban logistics. The key advantages are: (a) the flexibility, which is created by combining a common framework for various levels of regulation (in geofenced zones) with local implementation at the levels required; (b) a common framework that can be applied to any urban area, thus respecting national and municipal regulations while providing intelligent access restrictions to specific urban areas/neighbourhoods. Otte and Meisen (2021) conceptually sketch how such a control mechanism can develop based on computing technologies, allowing city governments to more dynamically manage urban logistics. This approach can make it easier and more attractive for cities to implement regulations and ensure that the implemented technologies and regulation frameworks are harmonised across cities. A shared standard needs to be achieved to create the scale required for low-cost implementation.

Specific groups of stakeholders would enjoy additional benefits:

- Policy-makers get opportunities to address actual problems of specific areas, thus obtaining a higher impact from their policy actions on congestion, noise, emissions and safety. The system easily allows for shifts in priorities of the local authorities. Intelligent access management systems provide a way to better data collection on urban commercial transport and make digital enforcement possible, thus increasing efficiency of enforcement measures.
- Transport companies have to deal with only one system nationwide, which automatically introduces measures relevant to the specific area. Vehicle navigation systems could be connected to automatically (re-)calculate routes and provide up-to-date information loading and unloading spaces.
- Ultimately, citizens would benefit from less congestion, less pollution and noise and increased safety. Also, the amount of information available would allow them to experience new levels of transparency about the city's processes and priorities.

Pathway 3: Digital Twins for Collaborative Innovation

The above-sketched developments of, on the one hand, a largely autonomous Physical Internet and, on the other, urban governments trying to establish some form of control over it, raise the compelling question as to how this confrontation could be managed. More precisely, in the specific context of this chapter: is there a role for computing technology to guide these opposing forces? Besides increasing efficiency and allowing means for control, the technologies above also allow advanced decision support, to both the logistics sector and governments. This development is known as *digital twins* and part of the *smart city* paradigm. A digital twin (DT) of a city entails a computerised representation, or simulation, of all the objects and activities inside the city at the same levels of geographical and temporal resolution as in real life. It digitally visualises the city and reproduces its behaviour, both autonomously as in response to external influences (Kaur et al., 2020; Raes et al, 2021) (see Table 16.4).

Digital twins are expected to have a profound impact on decision-making about urban freight systems, both from the public and the private side. Currently, conventional decision-making processes on both sides rely on rather slow cycles of information gathering, generation of alternative solutions, evaluation of solutions, decision taking, implementation and learning. The number of cycles per unit of time, or frequency of decision-making, is determined by the duration of each stage and the quality of connections. Typical frequencies

Table 16.4 Role of advanced computing technology in digital twins

Innovation	*Role in a DT*
Product and service sales platforms	Digital representation of markets
Advanced data analytics	Processes sensing data and helps to predict behaviour
Barcodes and RFID	Sensors to inform a DT
VR/AR applications	Supports communication of city visualisations
Transport and shipment information	Input to DT of real flows
Internet of Things	Sensors to inform a DT

differ between decision problems, roughly between once daily for trip planning to once in four years for infrastructure planning. An important effect of DTs is that they speed up each individual stage of the decision-making cycle and also connect them digitally. The ultimate impact could be a fully automated, fast and responsive decision-making process. Before this state is achieved however, the main change is that decision-making processes will be based on more transparent information and move from the current low-frequency processes to higher-frequency ones (Batty, 2018; Otte and Meisen, 2021).

Due to the detailed level of visibility provided by urban logistics processes, DTs not only impact the frequency of decision-making of actors, but also how these actors collaborate. Whereas traditionally models considered long-term processes and zonal level flows, today's models use detailed, micro-level simulations of individual parcels, including their strategic alignment in supply chains, business ecosystems and social networks (De Bok and Tavasszy, 2018; Stinson and Mohammadian, 2022). As our modelling capabilities allow emulating real-life processes in more and more detail, models are evolving from stylised representations towards full digital twins of real urban systems. A major advantage of this is increasing transparency about the everyday processes that decision makers are familiar with. Whereas in the past, managers and civil servants had to grapple with abstractions of cities invented by modelling specialists (with typical notions such as traffic analysis zones, discrete choice models, and network optimisation), they can now follow the daily functioning of the system, with a much higher level of face validity than ever before. Also, while models used to be targeted towards either public governments (focusing on fields of public interest like traffic congestion and emissions) or private companies (focusing on optimisation opportunities for their individual supply chain), current data-driven models are comprehensive agent-agnostic: as a result, all are looking at the same processes that can easily be observed in real life and will therefore be trusted more quickly by both sides. This is particularly relevant for innovation processes, where decision-making is traditionally problematic, especially in complex social-technological systems like urban logistics. A DT that is connected to sensors in the city allows a continuous measurement and evaluation of the impacts of innovations. Cities can act as living laboratories where innovations are introduced incrementally and experimentally (Marcucci et al., 2020; Quak et al., 2016; Thomke, 2020).

Conclusions

The digital revolution has accelerated the way in which logistics operations are planned and executed in the urban environment. It has also changed the landscape of urban logistics, in the sense that multiple technologies have allowed entirely new services to appear.

The long-term outlook is that urban logistics will become vastly more efficient and effective, through full visibility and automated coordination, in a system that is now labelled Physical Internet. From the public government perspective, cities are becoming smarter, which provides new capabilities for sensing the state of the city, be it concerning congestion, emissions or citizen satisfaction. Smart cities are also developing new approaches for control over activities by advanced forms of access control and traffic management. While the Physical Internet and Smart Cities, both spurred by digitalisation, could develop as opposing forces, the increasing visibility of urban logistics processes and their impacts could be beneficial for their alignment. Both will be reliant on digital twins of the real system, to manage their own decisions (dominantly private and public, respectively). Although perspectives from which these digital twins would develop differ, they will both make use of the same data, related to real-world logistics processes. In a setting of collaborative innovation, it would be logical to allow digital twins to merge, to arrive at major decisions on urban logistics together. If urban logistics is the place where the Physical Internet and the Smart City will meet, a shared digital twin could be the virtual arena where battles are fought out and constructive scenarios forward are designed.

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