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Digital twins for freight planning

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Contents

Abstract

In the contemporary fast-evolving urban freight landscape, policymakers, planners and freight operators are confronted with increasing complexity and reduced time to act in an informed way. Traditionally, models and ex-post data analytics were the key to provide information, but demand has grown for interactive and flexible models. Digital Twins (DTs) are widely seen as an important part of the solution. The chapter describes the recent evolution of information provision in urban freight transport, paints an outlook for the future of DTs and discusses necessary conditions for their realisation. DTs provide value by visualising the current urban system and predicting future states in function of relevant external influences and actions from stakeholders. As a relatively recent requirement, they should be able to reflect the different interactions between stakeholders including the temporal scales of decision making in logistics, and its impacts. However, to be able to forecast future states, such tools need to be built with the participation of their potential users that is, all stakeholders involved in urban logistics. In the case of complex tools like DTs, the process of development is as important as prediction capabilities, to make sure they accurately reflect the trade-offs present in decision-making processes.

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1. Introduction

Policy makers have always faced the challenge of managing the complex system that are cities. They rely on information from different conceptual and quantitative models, where they simplify reality to understand the system. As the complexity of the system has been increasing due to changes in the economic, social and environmental landscape, models have had to adapt as well to reflect these changes. Sustainability and social equity effects of urban freight transport growth has forced decision makers to involve business stakeholders and citizens more closely in policy-making. Moreover, the appearance of e-commerce and new transport technologies also motivated the need for quicker and more accurate modelling in order to be able to understand and respond to the impacts. Similar to passenger transport, the freight services sector has also been influenced by new platforms and services which only targeted a niche portion of the market, fragmented flows further and failed to address sustainability concerns, such as the emergence of crowdshipping.

With the emergence of modern computing facilities and improved data availability, new models could be built that resembled the real-life city more closely, with improved validity towards policy makers. Also, they could become connected to the multitude of sensors and data sources of the city and provide faster answers with visually attractive and understandable output. Because of the acceleration of data processing, prediction and communication, models suddenly became viable tools not only for long term planning processes, but also for shorter term decisions (e.g. access management for trucks) and real-time control (e.g. traffic lights). It is in this context that the logistic industry and cities adopted thinking developed for production to create a new, forward-looking vision for policy support models, in the form of Digital Twins (DTs) management (Grieves, 2014).

Essentially DTs duplicate or twin the city and allow to visualise and simulate the effects of different policies, in slow and fast cycles. The DT serves as a virtual counterpart to a physical entity or system, referred to as the physical twin (PT). The DT encapsulates all pertinent information necessary to describe and emulate the PT. As outlined by Grieves, 2014, the DT comprises three fundamental elements: the digital environment, the physical environment, and bi-directional data connections. These connections enable the process of "twinning," where the data of the DT entity are continually updated using status information from the PT, and vice versa, changes in the PT can be motivated or directly actuated by the

DT's simulation or optimisation (Jones et al., 2020). Fig. 1 depicts the relationships between the PT and the DT. Metrology, or the act of measuring the current state of the PT, and the twinning process, which involves altering the PT's state due to changes in the virtual environment, constitute pivotal aspects of this framework.

Each component of the DT corresponds to its physical counterpart. The digital entity serves as a virtual representation of its physical equivalent, while the virtual process encompasses the models and interactions occurring within the DT framework. Metrology aspects are integrated into the virtual environment, involving the measurement of model outputs and Key Performance Indicators (KPIs), whereas the twinning process involves updates from the PT incorporated into the DT. The models utilised in the DT are crafted with the objective of accurately represent the PT (Borchert and Rosen, 2016).

The research on DTs has seen a big boost in recent years (Abouelrous et al., 2023; Hakiri et al., 2024; Le & Fan, 2023; Nguyen et al., 2022; Zhu et al., 2023). This was enabled by the appearance of different technologies

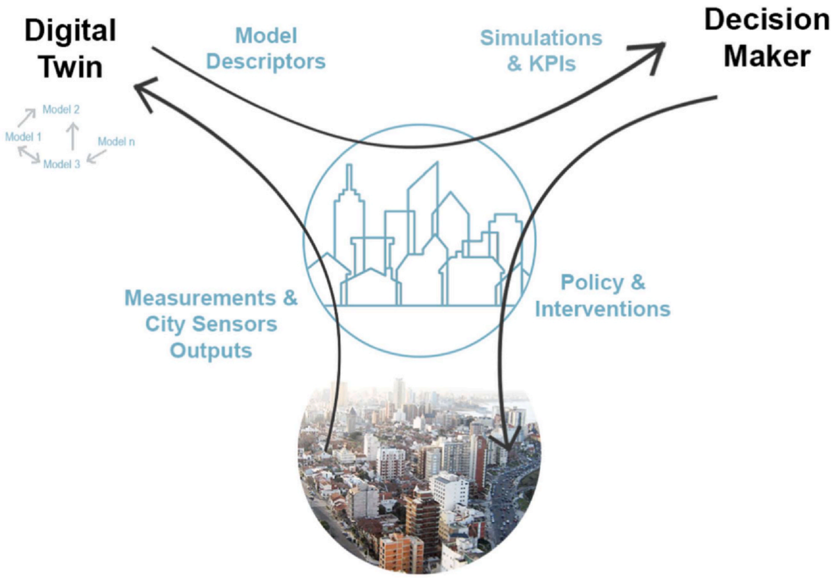

Fig. 1 Relationship between the physical and the Digital twin. *Own elaboration. Images from Aleco, 2009. Mar del Plata desde Torres de Manantiales. [WWW Document]. https://commons.wikimedia.org/wiki/File:Mar_del_Plata_desde_Torres_de_Manantiales_-_panoramio.jpg (accessed 07.28.24.); Vectorportal, 2023. Stock city outline vector and icon [WWW Document]. https://vectorportal.com/vector/city-outline/36128 (accessed 07.28.24.)*

that allowed to overcome a number of technological challenges (Rasheed et al., 2020). The first challenge of data management, privacy and security was solved by the development of digital platforms, cryptography and blockchain, which allowed to store and handle the data obtained in the ingestion process in a secure and decentralised way. Related to this, the development of 5G and Internet of Things (IOT) technologies allowed to have real communication of data and increase the latency of the synchronisation process. The improvement of sensor technology and data-driven modelling simulations has facilitated the possibility of real time modelling and replication of the twin. Lastly, relevant for the application of DTs for cities, it is the development of large-scale computation to process all the data and modelling implementation (whether through data-driven, Artificial Intelligence or theory driven models) needed for the DT to describe, model and predict the physical entity.

The data relationships between the physical and digital environments revolve around the twinning process (Jones et al., 2020), which entails synchronising the states (i.e. making current values of variables equivalent in both twins) between the digital and physical environments. This process involves bidirectional communication, wherein changes in the PT are communicated to the DT and vice versa, prompted by simulation results motivating changes in the physical realm. The frequency of twinning, known as the twinning rate or latency, varies depending on the overall cycle of measurement and communication between the physical and virtual worlds, ranging from rapid cycles in mechanical applications to more prolonged cycles in complex social systems such as city logistics (Weyer et al., 2016).

The systematisation of the twinning process is arguably what sets DT apart from traditional modelling strategies. Traditional modelling strategies typically involve an ad-hoc approach, with data collection and modelling processes defined on a case-by-case basis, resulting in lengthy cycles for evaluating policies. In contrast, DTs internalise data collection and evaluation processes, facilitating constant updates and rendering the modelling cycle more agile, allowing for adaptability throughout policy evaluation (DHL, 2019). The systematic ingestion of data and synchronisation of the virtual replica makes the trade off evident between the frequency of twinning and the accuracy of the twin (Tan & Matta, 2024). With a higher latency, one will need to ingest and process more data, which increases the cost of the data intake process in terms of bottlenecks in processing the data for the modelling. However, if the latency is low there is a risk that the physical replica diverges from the digital one in significant ways and reduces the capacity of the DT to represent the reality.

The benefits provided by DTs come from four primary value propositions (DHL, 2019). Firstly, their descriptive value enables stakeholders to comprehend the current state of the PT, visualising KPIs and processing real-time data. Secondly, they provide analytical value by simulating scenarios and deriving insights that may be challenging or impossible to measure directly. Thirdly, their diagnostic value aids in understanding the PT's functionality by identifying root causes of issues, informing evidence-based policy generation. Lastly, their predictive value facilitates the anticipation of future PT states, enabling decision-makers to simulate various scenarios and implement appropriate measures.

- Descriptive value: refers to the ability of DTs to provide a comprehensive overview of the PT's current state. This includes real-time monitoring of parameters, visualisation of performance metrics, and analysis of trends. For example, in manufacturing environments, DTs can monitor equipment health, production rates, and quality metrics, allowing stakeholders to make informed decisions to optimise operations and prevent downtime.
- Analytical value: pertains to the capacity of DTs to simulate complex scenarios and derive insights that may not be readily observable in the physical world. By leveraging advanced modelling techniques, DTs can predict the impact of changes in operating conditions, market dynamics, or resource availability. For instance, in supply chain management, DTs can simulate disruptions such as supplier delays or transportation bottlenecks, enabling proactive risk mitigation strategies to be implemented.
- Diagnostic value: involves using DTs to diagnose issues and identify their underlying causes. Through data analysis and correlation, DTs can pinpoint anomalies, inefficiencies, or failures within the PT. For instance, in energy systems, DTs can detect equipment malfunctions or energy wastage patterns, enabling corrective actions to be taken to improve performance and reliability.
- Predictive value: revolves around the ability of DTs to forecast future states of the PT based on historical data and predictive modelling. By simulating various scenarios and projecting outcomes, DTs empower decision-makers to anticipate potential challenges or opportunities and devise proactive strategies. For instance, in urban planning, DTs can

simulate population growth, traffic patterns, and infrastructure development, informing policymakers about future infrastructure needs and land use planning.

Considering the different ways that a DT can deliver value, it is expected that cities and companies start developing uses for this technology. In view of this, this chapter aims to give an overview of how DTs work, applications in urban freight and logistics and to reflect on how DTs can provide value in planning urban freight interventions. The rest of the chapter is organised as follows. Section 2 discusses the main components of the DTs, such as visualisation, modelling, and data. Section 3 shows some applications of the DTs in cities and logistics. Finally, Section 4 provides considerations regarding the application of DTs in cities.

2. Main components

2.1 Visualisation

As mentioned before, visualisation is one of the key ways that DTs provide value to the user. For example, Xu et al. (2022) use a virtual reality tool to monitor the effect of eco-driving policies in Melbourne, control the behaviour of drivers and analyse the impact. In this work, the drivers are embedded in a simulation of the driving conditions of the city to track their reactions. Under the definition that a DT is a replica of the physical element that allows for simulations of different conditions, it may be considered a DT. However, the visualisation aspect is not exclusive for DT applications and they can provide value outside the DT context. The generation of visual aids can support decision making in other ways as well such as map visualisations or extended reality. Calleo et al. (2023) use a GIS application to show the elements of spatial inputs by the decision makers and experts in a particular situation. The platform takes as input geographical information of the city and it performs a real time Delphi method to generate consensus across the stakeholders. This consensus is done real time while the stakeholders understand and view the impacts of the different policy alternatives. On example of the application of such tool is in the context of analysing the effect of installing new loading bays and parcel lockers in Dublin (Giuffrida et al., n.d.). The expansion of the use of extended reality is also a tool that can be used in the context of decision making across multiple stakeholders. There are also new tools to provide a 3D representation of a physical space to encourage stakeholder engagement in urbanist interventions (PaKOMM, 2024).

2.2 Simulation and modelling

Although they do not tend to have a central role in the description of the DTs, simulation and modelling are at the heart of the twinning capabilities of the DTs, and deemed as fundamental for the multiple applications (Halúsková, 2023; Rasheed et al., 2020). According to Halúsková (2023), the main difference between a simulation and a DT, besides the two-way communication between the physical and digital counterparts, is that a simulation builds on a unique run, while DTs make use of multiple simulations, both models and scenario instances, to provide decision support. This view highlights the centrality that simulations and modelling have in the DT concept.

To organise the models used in DTs for urban freight, Belfadel et al. (2023) propose a metamodel that characterises the different models and their application scope (Fig. 2). The metamodel groups the models into different dimensions: geographical, temporal, and typology. In the metamodel there are some other models that cannot be classified into any of the above, such as measurement of KPIs or other tools such as data collection instruments that are not classified in the above categories. The geographical dimension is the level of aggregation of the model. Zone level models are aggregations to any zoning system used, while the parcel/shipment level a fully disaggregated zoning. For example, a model that describes the demand for freight in a certain city/neighbourhood corresponds to the *zone level*

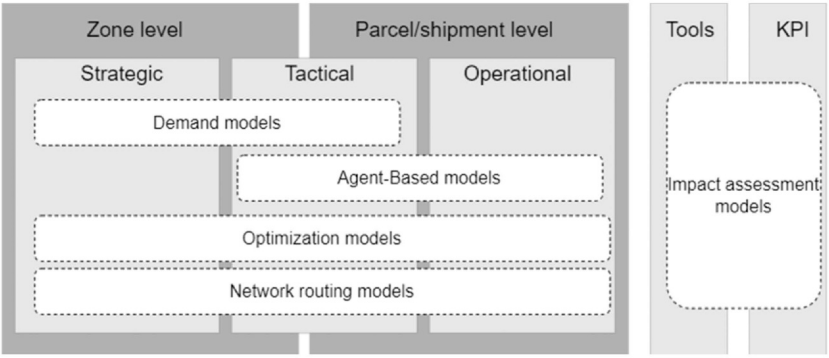

Fig. 2 Urban freight DT metamodel based on (Belfadel et al., 2023).

category, while a Vehicle Routing Problem (VRP) model that sets up the routing of the delivery vehicles in the city together with the routing belongs to the *parcel/shipment level* category.

The temporal grouping of the models is based on the classification in Tavasszy and De Jong (2014). The strategic level refers to the larger scale impacts of actions, such as changes in land-use, warehouse locations or population dynamics. The tactical level refers to the planning and set-up of the deliveries, such as the organisation of the deliveries for the next day, or the specific fulfilment decisions of a supply chain. Finally, the operational level models are the ones that describe the running of the actual delivery process, such as the VRP or network assignment models.

The main typologies distinguished in the metamodel are optimisation, network, impact assessment, Agent Based Models (ABMs), and demand models. Optimisation models deal with the minimisation of a cost-related function or, less frequently, with the maximisation of a revenue or level of service. The costs included in transport related applications tend to be vehicle-km and inventory costs, while attaining to some restrictions. The restrictions can be exogenous to the system, such as time windows for delivery, or endogenous, such as the number of vehicles or maximum driving hours. There are optimisation models that deal in a very disaggregate manner, such as VRPs, but there are also models that deal with long-term aggregate problems, such as warehouse location problems. The network models are the models that take a route or origin-destination pair and allocates it into a (road) network. They can be used to assign the VRPs into the road network to obtain the congestion or they can be applied into more aggregate long-term assignments when dealing with the connection between different zones in a more aggregate model. Impact assessments analyse and measure the impact of different policies (includes externality measurement). As a general rule, they rely on multiplying factors to convert physical outputs (such as number of vehicles and their speed) into a measurement of the impact. Some examples of these externalities are accidents, air pollution, emissions, and network congestion. ABMs are simulation models where each individual agent is modelled. The most typical agents in the urban freight context can be consumers, logistic service providers, shippers and receivers. These simulation models allow to include behavioural aspects of the individual and the interactions between the different agents. These models tend to be operational, dealing with the detailed movement of the agents throughout the day, but can also be applied in tactical settings to define how the fulfilment of the deliveries is done. Demand models are models that forecast the demand for goods. They can include the preferences of the population/firms and can synthesise a demand pattern according to their location and characteristics. These models tend to be in the more strategic and tactical time scales because they deal with long-term tendencies such as population and land use changes. One type of models that was not included as a separate category in Belfadel et al. (2023) are the data driven models because they can be included into the other categories based on their modelling objectives. These would include machine learning and other artificial intelligence forecasting models.

2.3 Data

Smart cities and the appearance of the IOT gives an opportunity to obtain status information of the assets on a high frequency. In fact, it is argued that the appearance of IOT together with communication technologies like 5G are one of the key enablers of DTs (Rasheed et al., 2020). The data from IOT can be of different nature such as network sensors, bike sharing data, public parking, traffic, pollution (Deng et al., 2021). The data for IOT is not just on for the city but can be used to track the different steps of the supply chain (Vilas-Boas et al., 2023). However, there is the risk that low data standardisation can hamper the improvement of DTs and their ability to have closer measurement and synchronisation with the PT, although there are several instances where this issue is being addressed (Hakiri et al., 2024).

DTs distinguish themselves from traditional modelling for the direct link between the physical counterpart and the digital one. The frequency and synchronisation method of the digital and physical entities is the key element to define when designing a DT. There is a trade-off between the cost of frequent synchronisation and the congestion during data ingestion and the bias (or divergence) that having a DT model that does not update frequently (Tan & Matta, 2024). This decision is naturally linked to the discussion on the timescale of the models applied. For example, if one is modelling the effects of a road closure in traffic, a high frequency synchronisation is needed. However, if one is interested in the effects of densification the city, a lower frequency of data collection can be used.

The ingestion of multiple data sources comes with a challenge towards the management of the different sources and standards. To address this, Liu and Tian (2023) propose a city data dictionary to create and manage the data standard systems. The compatibility discussion is also linked to having a common ontology of the processes (Liu et al., 2023). The storage and processing of this amount of information is also an important aspect of the creation of DTs. There closer the data collection is to real-time, it becomes more important to provide cloud processing and storage capabilities closer to where the data is generated to avoid saturation of communication. With IOT, the wireless transmission and storage of data comes with the security challenges (Wang et al., 2023). Even though the main novelty of DTs relates to the ingestion of real time data, contextual and more static data are also fundamental for the development of the DT capabilities. GIS information such as network data, warehouse locations, vehicle capacities and speeds, land-use information and population are some examples of such static data that are needed to contextualise the DT.

3. Applications

3.1 The city's built environment

In the city context the DTs tend to be used for visualisation and modelling of buildings. Schrotter and Hürzeler (2020) propose in the DT of Zurich add infrastructure modelling to the 3D representations of the city's buildings. The use cases that the DT was designed for is for the new zones' development plans, the planning of high-rise buildings, the analysis of urban climate. They promote digital participation and architectural competitions by providing visualisation of the effects of different policies or architectural interventions. Silva et al. (2018) propose the use of urban big data to generate a 3-tier architecture DT: a real time vision, data aggregation and service management. Highlighting the problems that big data poses and the challenges of real-time data processing, the data management system and preprocessing to simplify the inputs to the main modelling element. A remarkably interesting case is of the city of Xiong'an (China), where they built the city together with the DT (Liu & Tian, 2023). This includes the multiple subsystems such as infrastructure, public services, industrial areas and city planning.

However, there are more elements to urban DTs than the modelling of the architectural assets (buildings mainly) of a city. Ferré-Bigorra et al. (2022) propose a comprehensive review of the multiple users, life-cycle stage of the asset and the systems modelled. The users of urban DTs are not only the citizens and public administration, but they also include asset owners, asset managers and researchers. The subsystems included range from physical assets (buildings), weather and climate, pollution, services (sewage, electricity, water), and some transportation related, such as mobility, public transport and road networks. Combining all the types of DTs and of the different asset stakeholders and multiple systems models also support that the urban DT proposed by them is a combination and interaction of the DT of the different components of a city, similar to the concept of federation of DTs from Wang et al. (2023). The models used in the different twins included visualisation tools, but mostly simulation, optimisation or logic operators to monitor key variables (i.e. sensing whether a variable reaches certain critical value and alerting the user).

For the mobility element, Ferré-Bigorra et al. (2022) highlight video surveillance and public transport databases as data sources and a mobility simulation for the twinning element. This implies that the model scale used in their review of DTs is closer to an operational DT oriented to understand the current state of the city than for larger scale interventions. Kušić et al. (2023) use their DT to simulate the traffic conditions of highways, where they develop a network model that is calibrated using the traffic sensors in the motorways in real time. Deng et al. (2021) propose an urban DT for remote monitoring and support decision-making by policymakers using simulation, planning and early warning of critical variables. They identify different data sources for this, such as static data (e.g. mapping and networks), building infrastructure (for building information modelling technology), IOT dynamic data and blockchain for the transaction tracking and mechanism. The data would be processed with collaborative cloud computer for real-time response.

3.2 Urban logistics

3.2.1 Logistics

Logistics is used in this chapter as the management of the transport and warehousing of a single supply chain, in contrast to the term “freight transport”, used here in the context of public policy, where it focuses on the behaviour of multiple supply chains. Logistics systems are a strong testing ground for DTs. The ownership of data, processes and responsibilities tend to lie in a close-knit environment with significant control of the DT developer/user. The applications in this domain range from transport, production, packaging, warehousing, distribution to information processing (Zhu et al., 2023).

Le and Fan (2023) propose a framework for DT in logistics that comprises different layers and hierarchies. The layers relate to the different parts of the DT structure (physical layer, digital layer, and their communications). The hierarchy dimension presents the levels of integration between stakeholders, categorised in services, logistic systems and interconnected global supply chains. Finally, they add the dimension of the different stages of the supply chain, such as development, service provision and sales, predictive maintenance and use requirements of equipment.

As mentioned earlier in the chapter, visibility is one of the main ways that DTs add value to the user. As such, some applications highlight this feature, such as Vilas-Boas et al. (2023) for food industry supply chains, Thürer et al. (2022) for manufacturing and production logistics, Lee and Lee (2021) to visualise movements of vehicles and transport. Baalsrud Hauge et al. (2021) propose DTs so that user can visualise the paths of automated guided vehicles in the production floor. Coelho et al. (2021) use 3D visualisation for the movements of supplies inside the factory. The role of short-term simulation in logistic DTs is a recurring topic in these studies (Le & Fan, 2023). Thürer et al. (2022) propose using sensor data as input for the production simulations. Pan et al. (2021) propose a DT that focuses on the problem of the pick-up and delivery in the context of production. They solve a multi production unit, multi transportation and multi storage problem for an industrial park with synchronisation to the physical events. Zuhr et al. (2022) use a discrete event simulator to identify bottlenecks of the production plant focused on the internal logistic process in a production setting. Similarly, the DT proposed in Ferrari et al. (2022) simulates warehouse logistics. In the context of deliveries DTs, the use of simulations range from VRP procedures and GIS visualisation for construction logistics (Lee & Lee, 2021), the simulation of warehouse logistics (Coelho et al., 2021) and GPS systems and data to enhance last-mile delivery visualisations (Wanganoo and Patil, 2020).

The examples above deal with high frequency simulations for logistics and supply chain management problems on short timescales. This requires the modelling processes of the DT to be close to the assets and their interaction processes. Other applications can play in a broader range of time scales. Nicoletti and Appolloni (2024) propose a DT where they combine warehouse, transport, management, ICT and shared decision making. The interventions simulated are transport network design, network assessment (measurements of performance) and optimisation. The delivery network design (for example where to locate warehouse and inventories, delivery vehicle types) when launching a new product is a strategic decision that can be simulated in a DT with the measurement of the effect of adding/removing an arc (i.e. transport links) or modifying the capacity of a node (i.e. the size of a warehouse). The different scales of the problems (weekly, bi-weekly or continuous) handled also impact on the scale of the simulation and relate more closely to the framework in section [models] about urban freight DTs. Nguyen et al. (2022) propose a literature review of DT in logistics with the focus on how this technology unlocks the potentials of the physical internet. They highlight that the physical internet idea has had much more logistic focused, while the DTs had been more focused in production digitalisation and simulations of supply chain resilience. However, they expect that there will be more integration of both concepts for business ecosystem developments, sustainability aspects and cost/revenue management.

The DT's proposed in the literature can evaluate the potential impacts on the physical locations and supportive systems of a network when there are changes in demand and supply. This solution aids the assessment of the configuration of the current (or future) networks considering the expected fluctuations in demand or even simulate the effects of disruptions of the supply chain. In situations where the demand is known, it can contribute to real-time scenario building for the supply chain network by simulating the trade-offs between level of service and the costs of the network.

3.2.2 Urban freight transport

Even though there are a lot of applications of DTs in logistics and, even for company logistics in cities, DTs for policy-oriented urban freight applications are relatively scarce. These focus on city-level management of the entire system of multiple consumers and logistic service companies, which populate the urban environment. As an encapsulating concept, urban freight consists of multiple activities, companies, data sources, and assets that can be twinned. This generates the need for a common ontology in order to organise the different entities and relationships in urban freight. Some general ontologies have been developed for the context of ABMs (Anand et al., 2014), which could be seen as a first step towards developing a DT for urban freight. Moreover, a common ontology, together with the appearance of multiple individual DTs, such as the case that the different logistic service providers in a city has their own DT, allows the possibility of combining them into a federation of DTs (or internet of DTs) (Wang et al., 2023). This federation of DTs allows the communication across multiple different DTs creating a decentralised DT that can represent the multiple stakeholders and assets involved in urban freight.

The application of an ontology for an application in urban freight DT can be seen in Liu et al. (2023) and Abouelrous et al. (2023). Liu et al. (2023) apply a freight parking management strategy for Paris where they use IOT and smart city concepts together with parking management to improve visibility of the parking spots located throughout the city. To achieve this, they developed an ontology and a knowledge base that makes the DT shareable and reusable. The models used in the DT are an optimisation routing for the VRP of the vehicles and the parking spot selection. Similarly, Abouelrous et al. (2023) propose an ontology for urban freight including an AI component, then applied for a VRP case.

Another application comes from Madrid, where a DT was developed to enhance the decision-making of the logistic service provider and the municipality (Royo et al., 2023). This DT represents a two-echelon distribution network using parking places for deconsolidating into smaller and more sustainable vehicles in the city centre. The models used in this case are a network assignment (VRP style) model and a strategic two-echelon distribution centre model. While the more detailed VRP gives the exact routing and resources used, the more strategic model gives "rough" results that approximate the solution and gives some needed KPIs without a full simulation. A DT was also developed for Lyon to simulate the effect of an urban consolidation centre in the Confluence region for parcel deliveries. The larger regional depots in the area are located towards the south-east of the city and there is a need for a (de)consolidation centre in order to be allowed to use lower capacity (and greener) modes. They simulate using a detail ABM for the demand synthesis and location of customers, a VRP to solve the last-mile problem for the smaller vehicles and an emission calculator to estimate the effect that the smaller, greener vehicles would have if the new consolidation centre is implemented (Belfadel et al., 2023). More information on the model, data and results can be found in Sebastian Hörl, 2023. In the same framework of DT as described above, The Hague DT simulates the tactical decision making of parcel delivery companies and the effects of a crowdshipping platform. The simulation is done through an ABM that considers the behaviour of the different components of urban freight, including the individual behaviour of the different carriers and the different logistics segments operating in the city (De Bok & Tavasszy, 2018). Details of the specific applications can be found Tapia et al. (2023).

The DTs for Madrid, Lyon and The Hague run under the same framework developed in the Horizon Europe LEAD project (LEAD, 2023), meaning that the DT applications are instances of the same metamodel.

Fig. 3 shows the extraction of the models used in the examples above and their relationship to the different categories (see **models** section) and it illustrates how different types of models and model scopes can be combined in an urban freight DT. It is worth noting that the metamodel developed in the LEAD project contains more models and applications in other cities, such as Porto, Oslo and Budapest. The business process of the execution of a simulation and subsequent decision making is shown in Fig. 4.

It separates the process into 3 parts. The first one is the data management, that ingests data from sensors or APIs and handles contextual information of the city.

The second part is the execution phase, where there are two modelling functions. The first function monitors the sensors and triggers an update of the DT to synchronise with the PT if necessary. The second function triggers a simulation at request of the user. This simulation starts with the input of the configuration parameters for the runs and the selection of the suitable models from the model library depending on the KPIs required. This selection could be done either by an advanced user or by the DT using as inputs the KPIs needed and the data available.

The last part is the decision support system. This takes the results of the simulations and displays them to the user. This display is related to the [**visualisation**] section, where the impacts of the scenarios created by the users are shown, together with the relevant KPIs. Each scenario is saved so that multiple simulations can be compared and a policy decision can be made. For more details and insights on the technical decisions for building an urban freight DT, we refer to the paper by Belfadel et al. (2023).

4. Value of DTs for urban freight transport planning

A DT can bring value to policy makers and the stakeholders that are involved urban logistics. However, the examples mentioned above are either applications in very domain specific environments, such as the logistical cases focusing on single supply chains, or, as far as we are aware, very early implementations of DTs for cities. There is an argument to be made that the large 3D representation of cities are DTs, but these applications generally do not allow interventions relevant for urban freight transport policy. Earlier reflections on the capabilities of DTs to capture the essence of cities are critical. Batty (2018) argues that the DT, when applied within a social context, will not be able to reflect the social complexities.

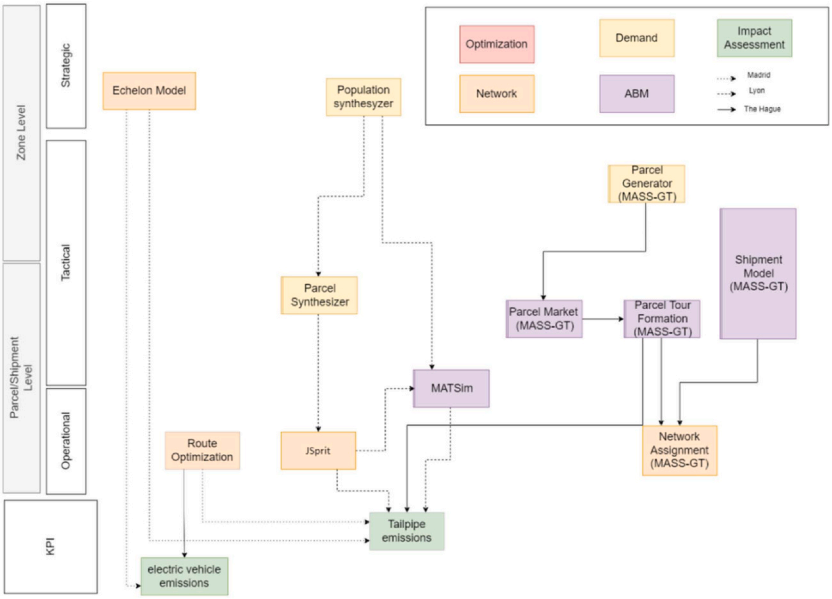

Fig. 3 Models used in the LEAD applications (own elaboration).

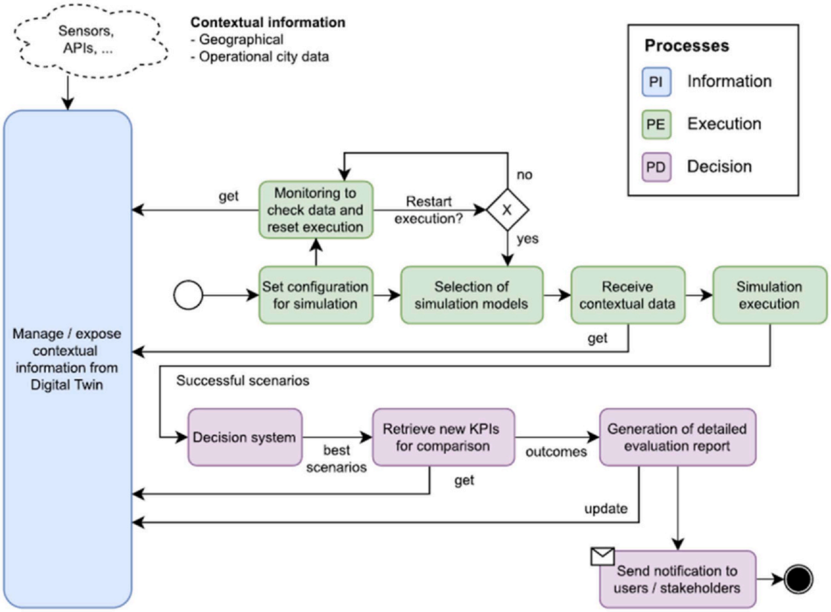

Fig. 4 Urban freight DT metamodel (Belfadel et al., 2023).

The slower time-dimension of changes in the urban system strongly contradicts the dynamic nature of the twin representation, ignoring the different latencies (or twinning rates) needed to see the effects of some changes in the physical structure. In a way, the argument is that the DT cannot be distinguishable from the models that underline them. Tomko and Winter (2019), reacting to a previous work by Batty (2018), agree with the main concept that the metaphor of DT might be too exaggerated, but are more hopeful that the application of "cyber-physical-social system" can actually be replicated.

Batty, 2024 goes further into the argument that the extra layer of difficulty related to the implementation of DTs in cities is that, in the urban context, the DTs are aiming to twin a social system. The processes that rule decision and impact the physical assets of cities is social and behavioural at heart and thus it is complex, dynamic, and, in many cases, even contradictory. Moreover, the different temporary scales that rule city dynamics also affect the resolution that the DT has. For example, land use changes have long term effects on cities. The effects that changing the land use can have on cities vary from changes in shopping related trips, such as buying products closer to home, the possibility of building a new depot or the densification of certain neighbourhoods to name some examples. All these changes happen at different timescales: new businesses opening in certain areas, or the creation of a warehouse are mid-term decisions, while population densification is a longer term one. A DT should be able to reflect these changes as well, although there might not be readily available sensor data that can closely monitor the changes in the timeframe within which the decision is being made. This contrasts with the effect of a road closure due to an event, like a marathon or a big football match. These changes affect people on the short-term operational level (i.e. how do they move from point A to point B) and can be simulated during the days before together with traffic management settings. During the day of the event, the DT is able to monitor real time how congestion appears on the network and be able to react quickly if anything did not go as planned.

Naturally, DTs for urban freight transport are part of this discussion. The multiple decisions in freight also fall into multiple time scales. A categorisation used in Tavasszy and De Jong (2014) of these decision-making processes divide them into 3 categories. The first one is the long term, or strategic category, where production consumption and trade related decisions are made, such as plant location, suppliers, and shipment sizes. The second decision-making tier is related to mid-term decisions such as shipment sizes, inventory policies and location and re-supply policies. Finally, the short-term period comprises mode decisions (in urban setting: road vehicle types, public transport, two-wheelers and walking) and the more operational choices such as route choice.

The above categorisation fits well into the multi-timescale problems that urban DTs face. The modelling tools that underline the DT functioning must match the scale of the problem that the model faces, as shown in Fig. 2.

Marcucci et al. (2020) highlight these challenges when they argue that since DTs rely on models and since by definition models are a simplification of reality it can never truly be a twin. They support the idea that a DT can get close enough to the reality to overcome most of the issues, except for the validity of the relationships between variables in the long term. Paradoxically, this is probably one of the main applications of urban DTs. The process required to design DTs for urban logistics goes beyond modelling and involves constant interaction with different stakeholders to generate value across the urban landscape. This allows DTs to become a tool not just for visualisation, but a tool for the co-creation of knowledge across the stakeholders. This is particularly important in the logistical innovation context because of their multi-stakeholder and multi-objective nature (as seen in Chapter 4), where innovations, and freight planning in general, are at risk due to the challenge of finding sustainable business models for all the stakeholders. When DTs are co-created in the context of living labs, stakeholders can validate the quality of the models. Beside validation during the co-creation approach, the stakeholders can also contribute with data (public and domain-specific), domain knowledge, the application of enabling technologies and supporting regulations (Rasheed et al., 2020). Following the categorisation of stakeholder engagement from Chapter 4, this corresponds to the "*empower*" category of methods, which relates to decision support activities such as workshops, freight forums and capacity building.

This relates with how the development and deployment of a DT for urban logistics can be made. The first step is to engage the stakeholders to understand not only their modelling requirements, but also give responsibilities towards the provision of data. From the modelling requirements and scenarios to be simulated, the models to be deployed are built and deployed in a common framework where they can be reutilised for future simulations (such as the one shown in Fig. 3). Once the use cases and the sequence of models are developed, a second round of stakeholders validation of the results is made, where they are able to give feedback, challenge the assumptions of the models and reflect on the results.

With a validated simulation engine, DTs can explore the effects of policy interventions, the introduction of new technologies, or new business networks and platforms for all the stakeholders. They allow testing of scenarios where the complex interaction between urban agents and obtain relevant indicators such as CO_2 emitted, congestion, potential revenues, and market shares. They are able to evaluate the market conditions for a complex system and test assumptions behind proposed business models or use cases. This simulation-based approach allows public and private stakeholders to efficiently deploy their resources and identify the consequences of new technologies, evaluate the conditions under which technology can be economically, socially and environmentally sustainable, and evaluate whether these conditions are acceptable for society. This way, they reduce the risk of damaging the existing business environment for an intervention which has a negative net effect for their city.

Finally, by showing the effects of policies, validated DTs can help to develop a narrative to drive communication within living labs and with external stakeholders. They can be key to unlocking green logistic innovations by simulating collaborative business scenarios that can show how value can be created and shared.

In urban freight transport many services target niche market segments. This can lead to fragmenting of transport flows and to lower overall efficiency. This effect may render interventions economically, socially and environmentally unsustainable. In a time when the public sector has few resources (monetary and time) to deal with an increasing number of proposed solutions and platforms, the challenge is to identify innovations that have a strong societal business case and not just a strong consumer focused narrative. It is in these conditions that DTs can have a strong use case to aid public sector to make sound, evidence based and (relatively) fast decisions.

5. Conclusions

DTs are digital representation of a physical entity that can mimic and forecast its states. DTs provide insights in four ways, by their descriptive, analytical, diagnostic and predictive capabilities. The key components of a DT are the visualisation element, the modelling core and the data that feed it. Coming originally from a production environment, they were conceived as a fast and responsive way to know the status of different production environments. As such, the first applications related to freight and logistics were supply chains twins, used for design and monitoring.

DTs in relation to traffic problems in cities started to gain traction with the development of IOT and the need to understand and apply more complex policies in an increasingly complex system. Applications range from simple visualisations to more complex monitoring of traffic and infrastructure assets. In urban freight transport, the panorama is less established. Data in freight is typically less available and the interactions across stakeholders in the cities are complex. This has resulted in fewer applications and generalisable DTs.

The application of DTs in cities and for urban logistics has its own challenges compared to those with the original purposes of DTs in a manufacturing environment, as the relevant context for cities is socio-technical. The inclusion of all public and private stakeholders, including the citizen, is one of the key challenging areas for the use of DTs in cities, where critical development tasks exist. These relate also to the different timescales involved in urban planning and dynamics. There are fast and slow changes that interact and co-evolve affecting social structures as well as the use of the physical assets. The question on how to set up feedback measurements of the long-term interactions using short-term sensors and how to disentangle the operational and strategic consequences of the evolution of urban logistics is one of the key technical discussions that DT developers have to face. Probably, for that reason, we might see DTs evolve more as short-term focused control towers, than as strategic management tools claiming to be able to solve cities' wicked and messy planning problems.

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