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A conceptual digital twin framework for city logistics

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ABSTRACT

Urban logistics is one of the key elements of urban mobility planning. The use of real-time information systems in logistics operations generates an enormous amount of data, nowadays used mainly for the purpose of monitoring and control of large flows of goods. At the same time, urban planners, business stakeholders, and city administrators are in need of adaptive, data-driven decision support solutions to address today's urban logistics problems. Recently, digital twins have received a lot of attention to support advanced experimentation, simulation and decision-making for on-demand logistics operations. Questions still remain on how to realize these for urban logistics management in a mixed public-private stakeholder context. We argue that this lack of a specific framework for city logistics with a model library for data mergers, linking physical and virtual data exchange, can compromise the timely adoption of digital twin technology. We contribute to filling this gap by presenting a systematic review of the literature, proposing a conceptual framework for digital twin applications in urban logistics, and providing use case scenarios for their demonstration. Together, these should advance the technical implementation of digital twins in a sustainable city logistics context.

1. Introduction

Today's consumer trends require reactive logistics systems that deliver personalized products at a low cost. Urban freight transport is essential for cities, and the surge of on-demand logistics is putting a noteworthy strain on last mile delivery systems that are growing at a rapid rate through large- and small-scale consumer platforms (Joerss, Schröder, Neuhaus, Klink, & Mann, 2016). However, the economic drivers to build more sustainable systems are weak (Allen et al., 2018). Consequently, cities are facing the likely downside of this "uberisation" of logistics. There is some apprehension about how the actual business will develop and what approach will be taken by the major actors, such as the introduction of tiny storage facilities in neighborhoods or the physical internet development (ALICE-ETP, 2020). It is therefore impossible to reliably predict the most probable outcomes for the next few years and to propose feasible policies.

To this end, data-driven models should run in conjunction with real-world experiments to replicate results and predict the consequences of response actions. The concept of Digital Twins (DT) can be used effectively in this regard, as depicted in Fig. 1. Technology enablers for building DTs include modeling, predictive analytics and decision-making methods, and the use of lifecycle-oriented knowledge with historical and real-time operational and city data. In the latest years, cities are already heading in this direction with a growing number of logistics living labs, which supplement the old paradigm of *predict and provide* (Marcucci, Gatta, Le Pira, Hansson, & Bråthen, 2020). Nevertheless, research on digital twins applied to transportation logistics is still very new and still developing (Marcucci et al., 2020). The applications of digital twin frameworks are mainly in the context of product management, shop floor or production management (Zhuang, Liu, & Xiong, 2018; Haße, Li, Weißenberg, Cirullies, & Otto, 2019, pp. 4–28), and the difficulty we face today is that the existing architectures are too generic to be used in logistics (Haße et al., 2019, pp. 4–28).

The lack of frameworks for model orchestration, data transformation and merging that connect the exchange of physical and virtual (simulation) data can compromise the adoption of digital twin technology for

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cities, which increasingly need to address city logistics problems with advanced data-driven solutions. Moreover, the complexity of the twinning for urban freight planning is influenced by long feedback loops that rely on multiple independent agents' interactions.

Therefore, we propose a comprehensive conceptual framework for a digital twin in urban logistics. With our framework, we address (1) urban and logistics modelers that study whole urban logistics systems or individual services who face the challenge of implementing their models in an integrated environment for decision-making, (2) public or private entities that strive to leverage their data by not only feeding individual models but maximizing their impact as part of such an integrated decision-making system, (3) developers of future digital twinning platforms, for which we provide a blueprint that already contains the major components to set up such a system. At the same time, we outline the specifics (for instance, in terms of time scales) that are relevant to the scope of urban logistics.

This work is an extended version of a previously published conference paper (Belfadel et al., 2021). We have extended our contribution as follows. First, we conduct a systematic literature review to thoroughly analyze existing work and put it in context. Second, we demonstrate in a generic business process how cities can leverage the targeted generic framework to create value case scenarios by using their specific models. For this, a generic model library that contains a set of models, when combined, allows the user to model different value cases, according to their needs. Third, we conceptualize a generic digital twin framework for urban logistics by proposing a general system architecture, investigating relevant modeling components, and providing a comprehensive list of existing open-source solutions. One of the main advantages of this framework are the different simulation model connections using connector functions. The models and connector functions are stored in a model library component, enhancing the continuous models' integration by adapting them to different use cases and city needs. Finally, we give use case examples for the proposed system.

The paper starts with a systematic literature review in Section 3. Afterwards, Section 4 focuses on the main components of the proposed architecture framework, the targeted generic business process, the meta-model for model categorization and each building block of the proposed framework as well as technical insights for its implementation. Section 5 combines the aspects presented in Section 4 to present use case examples for a digital twin in urban logistics. Finally, conclusions and future work are covered in Section 7.

2. Background

Since its introduction, different authors have defined DTs in different terms. The original definition was proposed by Grieves (2016) who defines a DT as a digital replication of a physical system that is depicted as a distinct digital entity but related to the physical system upon demand. The core elements of a DT are: (1) real world, (2) virtual world and (3) the exchange of data/information flow between real and virtual worlds.

Many applications of digital twin frameworks are found mostly in the context of the product, shop floor, and production management (Zhuang et al., 2018; Haße et al., 2019, pp. 4–28). The first definition of the DT was forged by the NASA to mirror the life of its flying twin (Shafto et al., 2012). From that moment on, several initiatives (Bickford, Van Bossuyt, Beery, & Pollman, 2020; Hatakeyama, Seal, Farr, & Haase, 2018; ISO, 2021; Lopez & Akundi, 2022; Qamsane et al., 2021) tend to standardise and construct conceptual and DT platforms in manufacturing-oriented digital twin systems. One of the recent published standards is the ISO 23247 (ISO, 2021). It divides the conceptual digital twinning system into four layers. The bottom layer depicts the elements of manufacturing that are observable. This layer depicts the elements of the production floor that need to be modeled. Yet, the difficulty we face today is that existing architectures are either too generic or too specific (Haße et al., 2019, pp. 4–28) to be used in logistics due to the complexity of the twinning as mentioned in section 1.

City logistics is one of the essential elements of urban mobility planning. The growth of e-commerce activities is a trend that has been reinforced by the COVID-19 pandemic. The ultimate objectives of introducing DT in city logistics are to improve the operation and efficiency of parcel delivery; to reduce costs and externalities through forecasting and predictions of future states; and to support advanced decision-making through the entire logistics lifecycle, while also fostering stakeholder participation via reliable real-life information. Thus, the adoption of DT in city logistics aims to help stakeholders to take decisions about the future implications of a given policy, aiming at supporting their information and enforcing the decision process (Marcucci et al., 2020).

Forecasting both behavior and reactions to structural changes and policy measure implementations in urban freight transport requires two elements. Marcucci et al. (2020) emphasize the usage of behavioral and simulation models to be used jointly when modeling such future behavior, especially when considering the public-private urban context.

DTs for urban logistics are evolved systems relying on three essential technical building blocks. First, relevant models for the physical counterpart under study are required. The models must be sufficiently detailed to meet the intended purpose. However, they should not be more detailed than necessary to avoid overfitting and support ease of use. It is worth mentioning that digital twins are not identical twins. As highlighted by Batty (2018), the notion of an exact mirror is "an idealization and aspiration that may never be achieved." Second, the object of the study must be described by evolving data as physical conditions tend to vary over time, whether it be traffic, air quality, or noise levels. Thus, informed policy decisions must be based on evolving datasets rather than point-in-time data collection that simply provides a snapshot of urban conditions at a given time. In this way, systemic changes over much larger time scales and patterns can be better understood. Third, like datasets, digital twins also require dynamic updates related to simulation models that update and evolve based on physical conditions

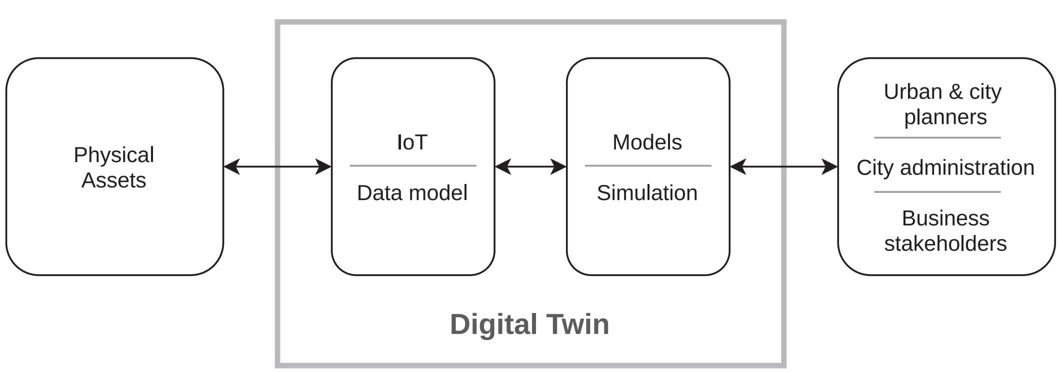

Fig. 1. A targeted digital twin environment for evaluating urban logistics policies.

(Kaur, Mishra, & Maheshwari, 2020). However, Kritzinger, Karner, Traar, Henjes, and Sihn (2018) and Sepasgozar (2021) identify the difference among a digital twin, a digital model and a digital shadow depending on the integration level.

2.1. Requirements identification and value case scenarios

To identify stakeholder needs, constraints and target scenarios, workshops were organized as part of a European project[1] to engage stakeholders in real-world experiences from different European cities and to identify the expected outcomes of DTs and the impacts on city logistics of the proposed value case scenarios. A value case scenario is defined as a set of measures and innovation being applied in one of the living labs. The results of the workshops also fed the definition of the generic business process model described in section 4.2.

All the Living Labs (LLs) identified, contacted, and engaged stakeholders from different local organizations, and assessed expected outcomes of the DT. One of the main constraints to be considered is the handling of different types of scenarios, all accompanied by a different set of case-specific, open-source software applications, for example MATSim[2] (a general multi-agent transportation simulation framework) or Visum[3] (traffic planning software designed for transportation planners to provide cities with a developed macro transportation model). Together, these models form an open-source model library (MLib) that can be applied in future DTs of other cities. The ML comprises different types of models that allow the platform to twin different cities and be able to test the different project strategies and policies.

As mentioned earlier, various use cases for digital twins in urban logistics are developed. The LLs use case scenarios include the “do nothing” scenario and four future scenarios. The first is used as a baseline scenario to compare the impacts on externalities of implementing certain actions. The second refers to the actions that will be implemented as a result of combining a set of logistical measures defined from the strategies and trends identified from the literature (Gatta, Marcucci, Delle Site, Le Pira, & Carrocci, 2019; Verlinde, Macharis, Milan, & Kin, 2014). Once the LLs approved the preliminary set of scenarios, the future scenarios were described and used to assess sustainability impacts and identify opportunities and threats. The results of these two activities help validate the scenarios.

We briefly describe hereafter two targeted value case scenarios of the cities, that are considered as an input for this research work for the design of a generic digital twin framework for city logistics:

- Lyon value case: In the south-east of Lyon, most of the freight operators are located in a 20 km radius from the Confluence district. The current situation calls for new spots within the district to host freight operations, close to core areas. In the meantime, flows should be concentrated to cope with this organization and to ensure the integration of new modes and the reduction of externalities. The Lyon LL will focus on parcel deliveries. It will include the use of an underground parking as a hub towards final customers through cargo bikes, autonomous droids and electric assisted handling tools. The goal is to reduce the number of trucks entering and parking in the district. For the public authority, the main KPI to be obtained from the Digital Twin is the fleet operating in the Confluence area and the emissions related to this traffic, while for the operators, the relevant KPIs are related to the delivery costs and fleet use. Regarding the targeted models, this LL scenario aims to use different simulation models such as MATSim or COPERT (for COmputer Program to calculate Emissions from Road Traffic – which is the EU standard vehicle emissions calculator).
- The Hague value case: The densification of the Central Innovation District (CID) and development of Binckhorst comes with the building of larger and higher department buildings. Besides the mobility of thousands of people, it brings logistical challenges such as “how to deal with the supply of goods to these buildings, such as groceries, parcels and furniture.”. The project will allow testing innovative solutions to generate a sustainable inner-city logistic service for parcels. Important approaches for sustainable parcel logistics include crowd-shipping solutions, platform-based approaches and public consolidation places like mobility hubs. Many times, these are stand-alone solutions, however, with no or limited integration with other companies. This LL aims to innovate by creating improved connectivity between different services and across platforms as a new proposition, to create an overall more efficient and sustainable urban parcel delivery system. Similarly to Lyon, the public authority is interested in knowing how much CO2 is emitted in the situations with or without platform connectivity. The sustainable logistics companies interested in validating their sustainable proposal and, more importantly, to be able to know the costs and benefits of integrating their logistical operations. Regarding the targeted models, this LL scenario aims to use different simulation models such as MASS-GT (de Bok & Tavasszy, 2018; de Bok, Tavasszy, & Thoen, 2020), which simulates the different aspects of urban logistics, externality measurement models such as COPERT (Ntziachristos, Gkatzoflias, Kouridis, & Samaras, 2009) and a noise model making use of a simplified methodology that will determine the percentage of residents in the study area exposed to noise emissions.

We follow the perspective of Wildfire (2018) and Batty (2018), where DTs are introduced as either being *reactive* or *predictive*. The first category describes models in which the real system is modeled closely and which operate on time frames that allow for near-real-time feedback of input signals in order to optimize its future states. Usually, this involves rapidly running models and focus on certain aspects of the system. In contrary, the second category can involve large interconnected, potentially computationally intensive modeling pipelines, which predict many aspects of the urban system on a rather long-term horizon. Such models allow observing the progression of the system given certain use case scenarios while taking into account complex interactions between system components, emergent behaviors and rebound effects.

Finally, the overall architecture work is built and consolidated using the TOGAF standard and its guidelines, which is an open, industry consensus framework for enterprise architecture (TOGAF, 2009). TOGAF provides an architecture development method and tools for assisting the acceptance and the production of architecture assets. It is founded on an iterative process driven by a reusable set of existing assets and best practices. The usage of this methodology ensures that the architecture is considered as a whole, taking into account business, information system, and technology architectures. This allows to provide a big-picture of the targeted generic DT framework for city logistics, its main business processes, the high-level architecture, and implementation aspects that are discussed later on in this paper.

3. Systematic literature review

This section aims to systematically evaluate examples, frameworks and tools that are proposed in the literature to construct, evaluate, implement and track pin-pointed policies in urban logistics. The evaluation results will be used for the conceptualization and consolidation of a conceptual digital twin framework for city logistics.

3.1. Research methodology

In this paper, we conduct a systematic literature review (SLR; Snyder, 2019; Kitchenham & Charters, 2007; Xiao & Watson, 2019) for

[1] https://www.leadproject.eu/.
[2] https://matsim.org/.
[3] https://www.ptvgroup.com/en/solutions/products/ptv-visum/.

the evaluation of recent research studies regarding the application of digital twin approaches in the research area of city logistics. The research subject, i.e., the conceptual boundaries, was defined based on the term “digital twin” and the related terms “IoT” in the smart city logistics context.

By including the sequential identification, screening, clustering, and evaluation of research-relevant studies in research-related areas, the SLR approach was selected because of its systematic, method driven, and replicable approach (Booth, Sutton, & Papaioannou, 2016).

The following Table 1 depicts the SLR protocol based on the recommendations of the Cochrane Handbook for Systematic Reviews of Interventions (Higgins et al., 2019) applied here.

The SLR further requires a definition of search criteria, databases, search terms, and publication period. In this study, we have used Google Scholar as the main source for the keyword search, because it was identified as the most comprehensive database for scientific publications in the areas of engineering and management science by referencing contributions published in other important databases in our research topic such as Web of Science and Science Direct.

In the first step, we identified the relevant literature for digital twin, urban logistics and smart city in the subject areas of engineering, business and management by screening the article title, abstract, and keywords. In this step, we included all kinds of document types and restricted them to the language English covering a period between 2015 and 2021. This step has lead to a result of 261 records. In the second step, we additionally focused on the studies that propose frameworks or tools of the digital twins, internet of things, and big data applied to city logistics for decision making. This has lead to a result of 133 records. In the third step, an evaluation of the papers is realized regarding the topic and our research objectives considering high-quality studies only. In sum, the final meta-search query was formulated as follows:

```
allintitle: ("city logistics" OR "urban logistics" OR
"urban planning" OR "delivery" OR "last mile de-
livery") AND ("iot" OR "digital twin" OR "smart city")
```

As a result, we have identified 27 papers as the basis for the further research process.

3.2. Results

Based on the quality criteria for empirical research (validity, reliability, objectivity, and generalizability), we assured the quality of the research results by coding the identified studies with level “A” (high appropriateness), level “B” (medium appropriateness), or level “C” (low appropriateness).

Table 1
SLR Protocol and content.

SLR Protocol	Content
Main Question	How to manage the complexity of paralleling real-world events with digital twins, to support experimentation, simulation and decision-making for urban logistics operations?
Objective	The objective is to search in the literature if examples, frameworks or tools are proposed to construct, evaluate, implement and track pin-pointed policies in urban logistics
Inclusion Criteria	(1) Studies that mention big data, digital twin, and, internet of things frameworks or tools applied in urban logistics; (2) Studies that mention systematic analysis of the literature to collect city logistics data for better decision making; (3) Studies that contain the keywords: IoT, Digital Twin, Decision making, Urban logistics, big data, urban or city policies
Exclusion criteria	(1) Study is not in English; (2) The paper does not mention any framework, tool, use case or literature review related to the digital twins applied to urban or last mile logistics
Specific Questions	Does the paper's main question involve the urban logistics area? Is cited in the paper a framework or tool for designing and assessing targeted urban logistics policies? Does the paper propose an approach to speed up transition through the usage of DT tools?

The selection was conducted in two stages by three researchers. In the first phase, the selection was based on the title and abstract of the studies only. In the second phase, the full text of the study was evaluated by the research team. In addition, reliability was calculated by assessing significant differences in results. Articles without significant differences were directly included or excluded from the search process. Articles with significant differences were re-evaluated by the research team to obtain unambiguous research results. Table 2 displays the total results of the SLR. (See Table 3.)

3.2.1. Descriptive analysis

In what follows, we analyze the relevant papers as identified above. Table 2 shows the distribution of the appropriateness of the identified studies, which was evaluated by screening the title and the abstract of the respective studies. Table 4 shows the distribution of document types based on the identified contributions. The following Fig. 2 shows the development of the relevant research studies from 2015 to 2021. We notice that this topic is getting more and more importance starting from 2020 with more than 24 papers published in this period.

3.2.2. Content analysis

We have grouped the selected contributions into 4 topics. The first topic includes papers in relation to the modeling in smart city logistics. The second topic discusses the usage of the digital twin in logistics. The third topic involves the contributions regarding the digital twin in smart cities. Finally, the last topic is about the usage of IoT for urban logistics.

In the first topic, Liu et al. (2021) introduce a freight parking management for last-mile delivery scenarios in a smart city. A graph is used to formulate the object relationships with properties that represent the elements constituting the physical infrastructure (in the sense of a digital twin), and an ontology is designed to add semantics to the structural description of the smart city logistics parking lot. The built model is implemented into an experimental digital twin platform that displays the different relationships between nodes, and offers a user interface to query the ontology store to find suitable parking places for the defined last mile delivery scenario taking into account relevant constraints.

In the topic of using digital twins in smart cities, Raes et al. (2021) propose an architecture that facilitates data integration and fusion for the physical and virtual data exchange in a smart-city digital twin environment. The authors propose a means to link the architecture with individual models and data to monitor and synchronize the state and behavior of the digital twin to perform various what-if analyses related to traffic, air quality or noise pollution through APIs. However, there is no possibility to create complex scenarios that combine and integrate several individual models. Lee and Lee (2021) look at the use of digital twinning in the context of modular construction. They present an interconnected system between a building information management providing progress information from a construction site and a GIS-based logistics simulation to assess potential risks in delivering modular building blocks. They emphasize the cost generated by blocks arriving too early and the resulting need for exact just-in-time deliveries. By repeatedly synchronizing information from the construction and production site and by repeatedly routing risk-avoiding trajectories for the

Table 2
Total research results of the systematic literature review (SLR).

	Papers
Total studies	133
Not relevant	106
High Appropriateness	8
(DT for Smart city logistics)	
Medium Appropriateness	8
(IoT and Big Data for Smart City logistics and Decision Making)	
Low Appropriateness	11
(IoT for logistic systems)	

Table 3
Distribution of document types.

Type of document	Records	Records [%]
Conference Proceedings	12	44.44
Journals	10	37.03
Books	5	18.54

Table 4
Excerpt of additional implementation tools.

Component Type	Implementation Tools
Data & Model Management System	Docker, Kubernetes, Apache Kafka, Apache hadoop, Apache Spark, Apache Flink, Apache Mahout, Eclipse DITTO
Context Entity Manager	Fiware Orion Context Broker, Scorpio Broker, Orion-LD Context Broker, Stellio Context Broker
Decision System	Bayesian Inference Techniques (Python)
Simulation Configuration & Environment	Ansible, SLRUM, KVM
Dashboard & APIs	Grafana, Postman APIs
Storage System	RDBMS, InfluxDB, MongoDB, Hadoop HDFS, HABSE, hive,
Cloud environment	Cloudify, OpenStack, Cloud Foundry, Apache CloudStack, Docker

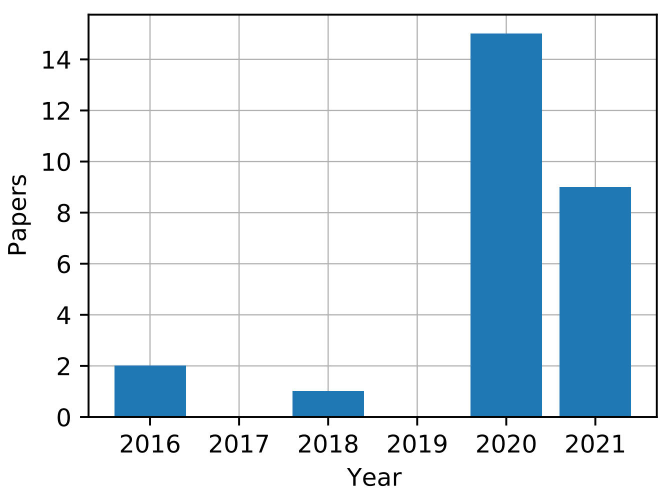

Fig. 2. Development of the relevant research studies 2015–2021.

delivery trucks, the aim is to reduce those delays. In (Schrotter & Hürzeler, 2020) a digital twin for the city of Zurich is presented. The authors propose an open 3D model of the city's building stock. It is continuously updated to allow for analysis and future planning applications. They emphasize their focus on the full life-cycle of data acquisition and updates within the system. Feedback loops are only envisioned on a conceptual and long-term planning level, but not in an automated way. Finally, after reflecting on the issues regarding the challenges and opportunities that IoT poses for smart cities, Silva et al. (2018) identify the need to create a flexible architecture that can allow reliable and efficient data management for real-time decision-making. The authors propose a three layer architecture and highlight the importance of having a strong data management component to handle the increasing volumes of information and making them usable. While their architecture focuses on the processing of big data, they lack an explicit modeling framework for the specific services offered, which can be an issue when dealing with urban logistics, where decisions on different time-scales interact.

Regarding the topic on the usage of digital twin in logistics, Pan et al. (2021) introduce a digital twin to deal with the increasing complexity and uncertainty of delivery systems with a focus on production logistics in an industrial park setting, where they aim to connect different units and agents. The presented architecture consist on three layers: (1) a Physical object perception layer, where the data is ingested and processed; (2) the Virtual model simulation level, where the virtual imaging of the physical objects is done and; and (III), the Synchronization system control layer, where the evaluation of the execution status is performed. To meet the social and ecological challenges of today's city, it is necessary to put in place policies that respect the individual circumstances and specificities of the areas concerned. Therefore, Belfadel, Hörl, Tapia, and Puchinger (2021) introduce a conceptual framework for the usage of digital twins in last-mile city logistics to help to interpret the logistics network dynamics in the city and the outcomes of the introduction of specific innovations. They propose a first approach to digital twins deployment for city logistics.

Finally, the last topic of selected papers is about IoT for urban logistics. In (Wanganoo & Patil, 2020), a digital twin for last-mile parcel deliveries in the United Arabic Emirates is conceptualized. In this particular context, last-mile deliveries are difficult to implement as addresses are not given by zip code or street name. The authors proposed an integrated system by which parcels can be tracked using a QR code, which is connected to a GPS-based location that is transmitted the day or hours before the delivery by the customer.

3.3. Discussion

In the previously identified contributions from literature, models are intertwined with smart city domains (i.e., building, environment, health) receiving input from multiple data sources. Dynamic correspondence linking a digital twin platform with models and data makes it possible to monitor and synchronize the state and behavior of the digital twin with the physical environment being mirrored, however this link is mainly a one-way link going from the physical world to the digital objects that are considered as digital shadow (Kritzinger et al., 2018). Very few papers consider the bi-directional communication.

In addition, very few papers have considered the usage of digital twins for urban logistics. The depicted decision systems from the presented state of the art are not well specified regarding the added value that those systems will provide nor any description of ongoing experimentation or example that might improve decision making in the domain of urban logistics. To validate such architecture, Hopkins & Hawking (2018) underline the importance of digital twinning in logistics and the need of use cases.

Finally, one big challenge to consider while designing our digital twin framework for urban city logistics is with regard to the twinning rate or what is considered as high and low-frequency time horizons by Batty (2018). In urban logistics, several kind of data exposition have to be managed, spanning from a very low rate data such as time series data coming from sensors of daily traffic to socio demographic data that are updated once a year (or more).

4. Digital twin framework for city logistics

4.1. Generic business process model

This section presents and analyses the targeted generic business process enabling the exploitation of DTs for City Logistics. First, as mentioned in Section 2, we realized workshops with relevant city logistics stakeholders and defined relevant value cases and real-world scenarios (description of the context, together with the actors, territories and companies involved, the main problematics they are facing and the targeted goals). Then, we identified the common future workflow that is shared between all the value case scenarios, and that is generic enough to be used by any other city along with their specific simulation models (see example in Section 2 and related models). This is to support experimentation and decision-making and create value for all different stakeholders.

The generic business process is depicted in Fig. 3. The first task (Data process, PD) manages the contextual information from the physical twins, and keeps the data updated during the whole lifecycle of the entire process. In addition, it enables to push updated contextual data to the linked physical twins, in case a stakeholder needs to update the state of the physical twin. The second pool (Execution Process, *PE*) describes the workflow that manages the user tasks and model configuration. These tasks enable stakeholders to construct simulation scenarios, with a possibility to choose and configure simulation model properties linked to it. The specific task *Monitoring* initializes the data monitoring (if applicable in the modeled scenario) to check the received data from physical twins and restart the simulation when a certain configured threshold is reached. The third and last pool (Decision process, PD) describes the workflow managed by a decision system. It receives the outcomes of the simulation as a set of successful scenarios. Then the decision system selects the best strategies among produced scenarios. Finally, the stakeholder that has launched the simulation scenario is notified when a generation of a detailed evaluation report is produced. This to compare the produced KPIs (from simulation) with the ones calculated based on a refreshed contextual data of physical twins. It is important to mention the bidirectional communication between the digital twin and its physical counterpart that is materialized through the link between the outcome of the best scenario and the PD task that allows to publish the updates to the physical counterparts in the real world. As depicted in this business process, there is a need to manage and integrate several kinds of simulation models in a given scenario. Consequently, a model library with a flexible approach is needed to categorize the urban freight system models, describe them, and most importantly, provide a means to handle all the transformations needed to transform the outputs of a model into another one.

4.2. Conceptual framework

Fig. 4 presents the DT framework for urban logistics, which is divided into three main layers. The left layer (*Physical World*) represents the sensors and external entities such as *Sensors and IoT Entities*, *City Operational Data* and exposed *APIs*. The middle layer (*Data/Model Management System*) consists of two main elements: the DIS (*Data Ingestion System*) and the MMS (*Model Management System*).

The DIS provides a solution to the need depicted by the *PI* task of the generic business process (see Fig. 3) that manages the contextual information from the physical twins and exposes the twinned data through web APIs to the other framework's internal components. It is intended to ingest the contextual entities (through the *Data Ingestion Manager* and maintain the digital twins updated, managing bi-directional connections with the associated devices that are exposing the contextual data via the *Device* and *Protocol Manager* components. This allows the management of the communication protocols to the physical counterpart and the exposition of this contextual data to the *MMS*. Due to the heterogeneity of the possible physical twins (cameras, sensors, open data, …), several protocols (HTTP, MQTT or AMQP managed through an IoT platform or an IoT agent[4]) and data format (and the storage by extension) might be involved at this level.

Since a digital twin needs a detailed model of its environment and its physical counterpart, DIS provides the ability to enhance the DT framework and related artifacts with descriptions that are based on semantic annotations or standard ontologies by means of the *Semantic Manager* component. See (Anand, Yang, van Duin, & Tavasszy, 2012) for an urban logistics ontology. This enables the use of business-oriented specific semantic models to provide a detailed and integrated view of all relevant artifacts, thanks to the use of a unified urban freight ontology that might be used by any model in a simulation scenario.

The MMS brings a response to the need illustrated by the *PE* and *PD* tasks (see Fig. 3) to integrate multiple types of simulation models in a particular scenario. The MMS consists of several components, including the *Model Library Manager*, which provides an outline of all of the available models, as well as their specifications and the connections between the models, and the key performance indicators (KPIs) that are useful for decision making. Please note that all data provided to MMS components during the configuration or simulation phase comes from the *Context Entity Manager* which exposes all physical counterpart's data to MMS components via web APIs.

The *Scenario Manager* allows the registration of what-if scenarios and their related models and configuration (model parameters, contextual data and expected KPIs). The *Model Integration and Orchestration* aims to orchestrate the models by connecting the datasets and the outputs from one model to another based on the what-if scenario configuration. The *Simulation Configuration* component is intended to manage the setup of the simulation environment in terms of technical aspects (parameterization of a virtual machine, technical libraries, etc.) As for the *Simulation Environment* component, it is a virtual execution environment generated on the basis of the simulation configuration. This component uses containerization and virtualization to create dynamically an execution environment for every scenario in order to execute the simulation and to collect the outputs of the scenario.

Digital twins offer real-time communication among assets and systems. The challenge is to know how the data is then processed to provide true added value. In this context, the value added is provided by the KPIs that are tailored precisely to the intended application. For this purpose, the final component of the MMS is the *Decision System* which aims to decide what results of the performed what-if scenario are most likely to be achieved. It considers the key performance indicators of a defined scenario and then recommends the required interventions in the physical world via the DIS to reach the predicted outcome. This decision system constructs its knowledge using different inputs such as model outputs, scenario parameters, model parameters, contextual data and predicted outcomes.

The remaining component is the *Storage system* for handling general storage such as what-if scenarios, scenario configuration, models and related data, or an ontology store (DuCharme, 2013) related to the use of the semantic manager component.

4.3. Model library and meta-model

The multiple value case scenarios that are considered in the generic business process model needs a flexible approach to be able to accommodate them. For this, a generic model library (MLib) that contains a set of models that can represent different aspects of the urban freight system. The objective of the MLib is to store multiple models that, when combined, allow the user to model different value cases, according to their needs.

In this work, The MLib is conceived as collection of models, where different model types, languages and frameworks can be included. This means that the models included can be theory driven, data driven, AI based or any other type of model. The models in the MLib are connected with connector functions that handle all the transformations needed to transform the outputs of a model into another one. These connectors work in a 1-to-1 fashion, making explicit connections. This has the advantage of increased modularity of the models (the model implementation do not need to change much from their original form to be included), makes data transformation invisible to users and avoids defining an unified urban freight ontology that affects every model.

To assist the user in the model selection, the MLib is organized in the Meta-Model (M2) according to its role in a broader city logistics framework, where an instance of the M2 is a set of models that

[4] An IoT agent is a component that allows a range of devices to feed their data to be handled from a context broker by using their own native protocols.

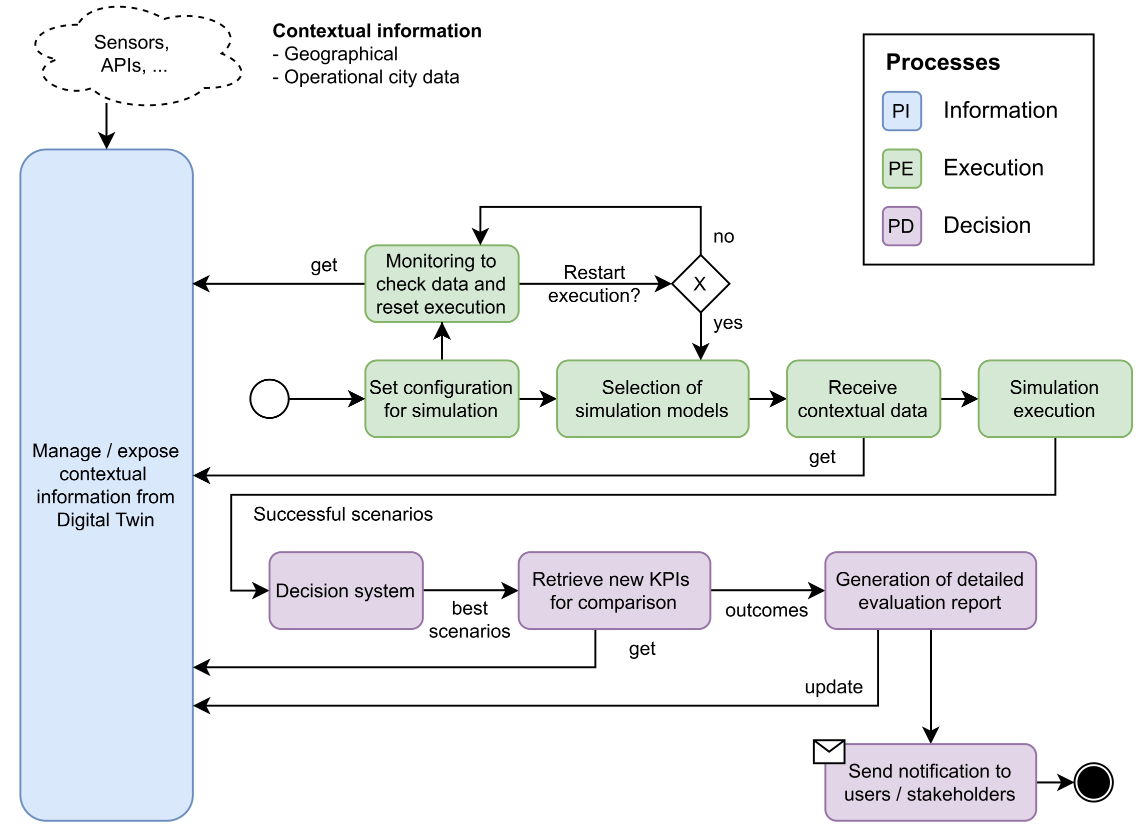

Fig. 3. Targeted business process.

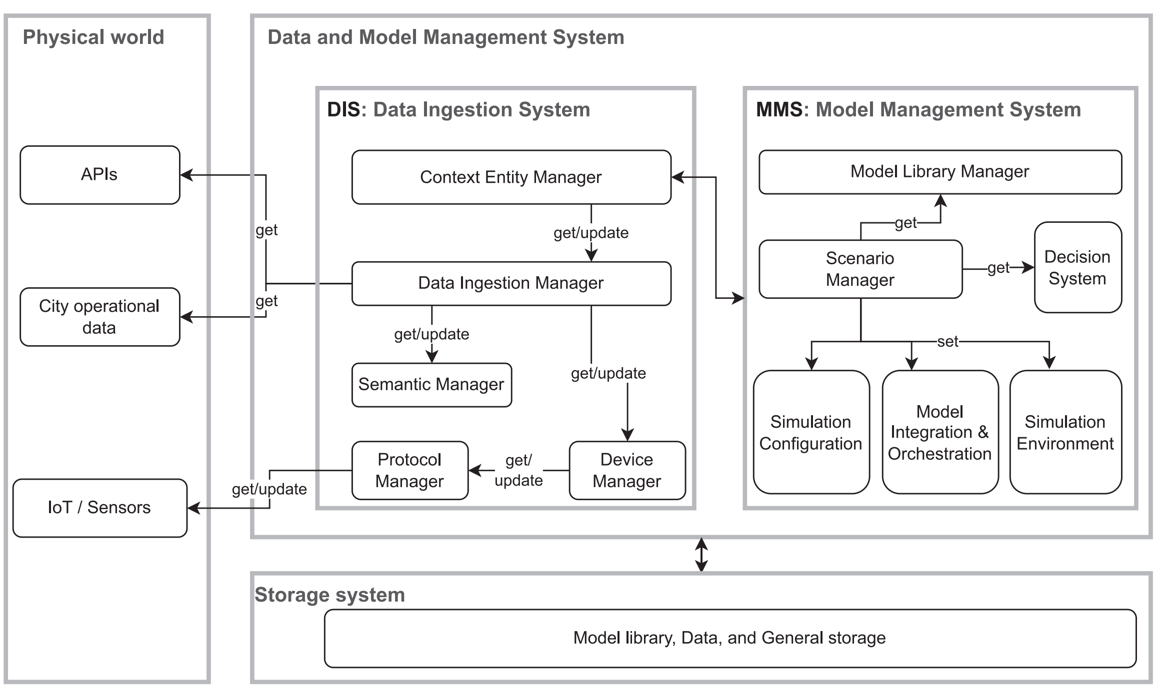

Fig. 4. Proposed framework.

represents a value case. As highlighted by Wildfire (2018) and Batty (2018), the time horizon of the model should match the time horizon of the city activity it wants to replicate. Thus, the M2 is organized by the time scope of logistic decisions: Strategic, Tactical and Operational (Langevin & Riopel, 2005; Tavasszy & de Jong, 2014) and by the resolution of the model: Zone or Parcel/Shipment level. Strategic level models are models that deal with long term decisions, such as demand trends and depot locations. Tactical level models define how the fulfilment processes are done. Finally, operational models deal with routing and delivery. This classification allows the user to choose the model that better represents their value case. Additionally, an extra category for models specifically designed to evaluate the outputs of the other models and convert them into KPIs that are useful for decision making. The current version of the M2 was developed according to the needs of several European cities of the aforementioned European project. The models in the MLib were further categorized according to their method, such as optimization, demand models, network models, Agent based models, impact assessment, and routing models. By being aware of the modeling methods used, the user can have more detailed knowledge and control of how the DT is replicating the targeted freight system. Fig. 5 shows how the models are categorized.

4.4. Framework implementation and technical insights

This DT framework might be built on top of existing open source cloud computing technology. It can apply containerization techniques like Docker[5] and Kubernetes[6] for use case model integration. Regarding the cloud environment, several cloud solutions exist in the market. For example, the hybrid stack could be provided by Cloudify,[7] can integrate cloud and local environments. Other existing platforms are OpenStack,[8] Cloud Foundry,[9] and Apache CloudStack.[10] Classical approaches adopt the idea of deploying full virtual machines (KVM[11]).

For the *Data and Model Management System*, a job scheduler can be employed over Docker/Kubernetes APIs, with a solution to handle data ingestion such as Kafka backbone, along with an open source framework for creating and managing digital twins in the IoT environment such as Eclipse DITTO[12] or Fiware Orion Context Broker[13] for the *Context Entity Manager*. For the *Decision System* (component of the *Model Management System*) one can employ Bayesian inference techniques coded in Python. Regarding the *Simulation Configuration* and *Simulation Environment* components, solutions for IT automation to configure systems, deploy software and orchestrate IT tasks might be considered such as Ansible,[14] SLRUM[15] and KVM.

For the connection of the physical world with the data and model management system, there are several front-end with open source solution for creating customizable dashboards (APIs) such as Grafana[16] technology tools, that is widely used to compose observability dashboards with metrics, logs, and application data.

For the *Storage System*, different solutions may be considered. For example, because sensor data can be produced very quickly, a traditional database may reach its limits in terms of processing speed and size rather quickly, requiring a different approach to managing this type of data. In this situation, big data solutions are required to achieve the necessary speed and scalability. Time series database such as InfluxDB,[17] or document oriented database like MongoDB[18] may be used for the querying and storage.

5. Use case example

In the following, we elaborate a use case that is based on the proposed digital twin architecture. As before, we base our considerations on the distinction between predictive and reactive models made by Batty (2018) and Wildfire (2018). The former describes a detailed modeling of the real system to predict or perform a scenario-based analysis of the (longer term) future with focus on complexity and a systemic perspective. The latter describes a sufficiently accurate model that can be run quickly in order to engage in a near real-time exchange with sensors and actuators in the real world.

The use case considers the management of an Urban Consolidation Center (UCC). Whenever upstream logistics operators intend to deliver goods in a specified area in the city, they need to pass these goods though the Urban Consolidation Center, which, in turn, organizes the last mile delivery in the area. The delivery can be performed, for instance, using cargo-bikes or future electric delivery robots. The goal is to minimize emissions by making use of sustainable means of transport and aggregating flows from multiple upstream operators.

Following the dichotomy of reactive and predictive digital twins, the UCC operator is interested (1) in efficiently dispatching its vehicles and (2) making sure that longer term needs such as increasing the vehicle fleet can be detected well in advance. The individual UCC case should be understood as being integrated in a larger urban logistics digital twin with other use cases, data interfaces and models. However, already the individual case allows us to demonstrate the interaction of our architecture components on a realistic example.

The general business case for the UCC is shown in Fig. 6. It includes three models:

- The **VRP model** describes a solver for Vehicle Routing Problems (VRPs). Its first input is a list of transport goods that need to be picked up at the UCC and delivered to their final destination. Its second input is a list of vehicles with their current location and charge (if they have already picked up some good). Third, the model may make use of information on the travel times in the underlying road network. The task of the VRP solver is to find relevant routes through the network and ideal sequences of pick-up and delivery stops. The solution may be based on different objectives, such as minimizing the incurred delays for the deliveries or minimizing the driven distance (and costs).
- The **Traffic model** is a network model that is used to predict travel times in the urban road network. Its inputs are current and historical vehicle trajectories through the network that may be considered with different weights. The goal is to fuse the trajectory information (locations and timestamps) to obtain an accurate prediction of travel times in the next few minutes or hours. The model should be able, for instance, to detect unusual levels of congestion on special occasions and, thus, intelligently adjust its predictions.
- The **Demand model** is used to perform longer term predictions. Its input are historical daily records of processed goods flows. Using this information, the model is able to predict general and seasonal trends on the total daily transport demand for the UCC, but also demand surges for specific periods of the year (such as Christmas or Black Friday).

Each model takes a specific role in the digital twin. The **Traffic model** is an auxiliary component which is constantly fed information to observe traffic and provide valuable information to the VRP model. The **VRP model** itself observes the current state of the system in terms of active vehicles and current demand. If new transport requests arrive, the model should react to them and integrate them into the planned vehicle itineraries. Finally, the **Demand model** makes use of historical information to perform longer term predictions of the daily parcel demand and test (using another instance of the VRP model) whether the future demand can be served with the planned vehicle fleet. It, hence, takes the role of future fault detection. All models are managed by the *MMS* component through its *Model Integration and Orchestration* which is able to configure those models given their individual input and output data streams and connect them where necessary. The input data and output

[5] https://www.docker.com.
[6] https://kubernetes.io.
[7] https://cloudify.co.
[8] https://www.openstack.org.
[9] https://www.cloudfoundry.org.
[10] https://cloudstack.apache.org.
[11] https://www.linux-kvm.org.
[12] https://www.eclipse.org/ditto.
[13] https://fiware-orion.readthedocs.io/en/master/.
[14] https://www.ansible.com.
[15] https://slurm.schedmd.com/documentation.html.
[16] https://grafana.com.
[17] https://www.influxdata.com.
[18] https://www.mongodb.com.

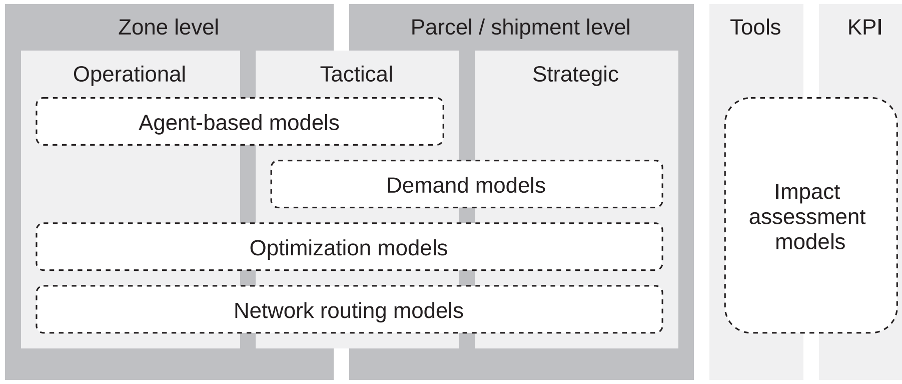

Fig. 5. Structure of the meta-model.

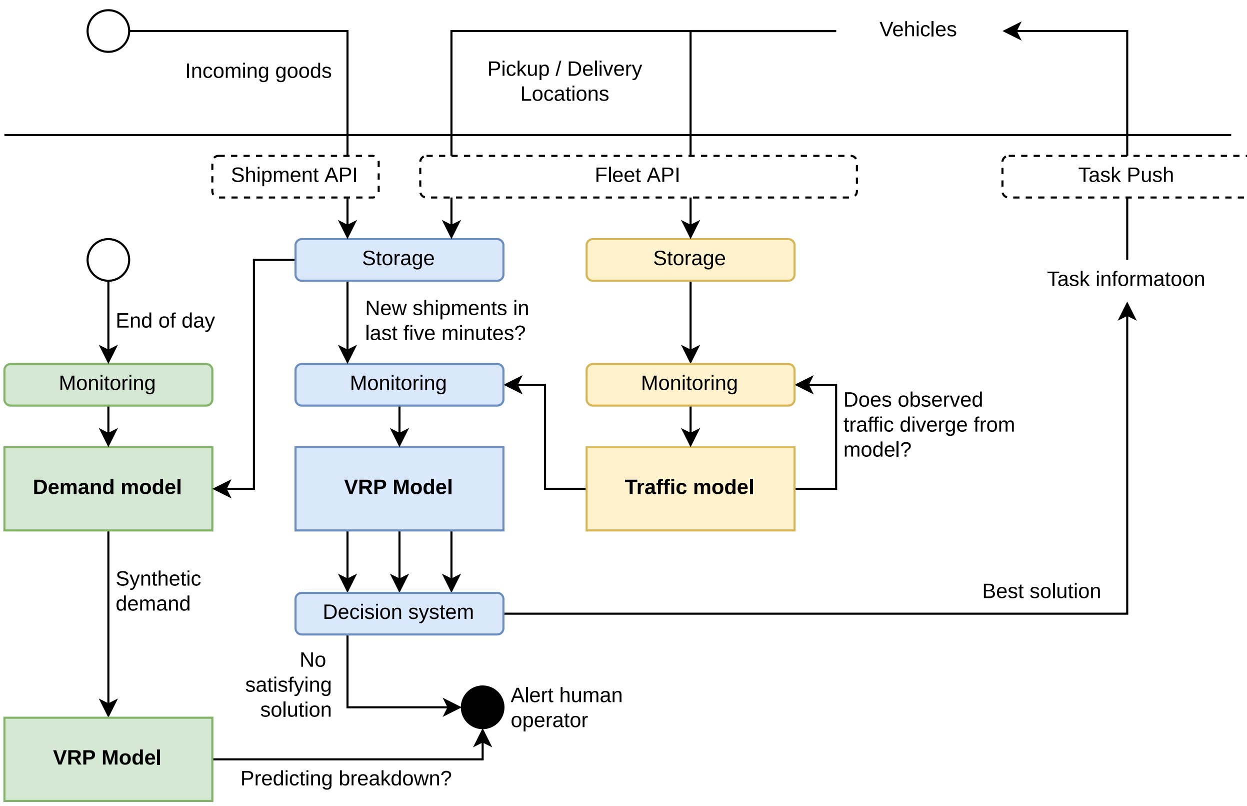

Fig. 6. Use case example for an Urban Consolidation Center.

data is obtained from and send to the *Storage system* component of the digital twin platform.

The models receive and send information through various interfaces that are managed by the *DIS* component that keeps the digital twin updated. In the specific example, we defined two APIs and a push service:

- The **Shipment API** manages the interaction with the upstream operators. They are asked to announce incoming flows to the UCC well in advance so that they can be processed without delays. Using the *Context Entity Manager* component that keeps the digital twin model update, the upstream operator communicates (and potentially later updates) information on the predicted arrival time at the UCC and the list of last-mile item that need to be delivered (`item identifier`, `destination address`, optionally, `desired delivery time`). In the real world, each item (parcel) should be tagged using a QR code so that the on-site operators can assign them an internal `delivery identifier`.
- The **Fleet API** manages the interaction with the UCC's vehicle fleet. Through the *Context Entity Manager*, the vehicles submit frequently their current positions. This allows to construct the vehicle trajectory by saving the positions and their respective timestamps (`vehicle identifier`, `location`, `timestamp`). Besides the location endpoint, there is an endpoint that allows the vehicle operators (or the vehicles themselves in the case of robots) to confirm that they have picked up or delivered a delivery. For that, they communicate the respective event (`pickup / dropoff`) and the `delivery identifier`.
- Finally, there is the **Task Push Service** to which all UCC vehicles are connected. The service can update the vehicles trajectories by sending them a sequence of tasks that can be `pickup` or `idle` (which always happen at the UCC) or `dropoff` (which happens at

the delivery destination). For a sequence of N jobs described by (`stop type`, `delivery identifier`), the vehicle receives a list of $N-1$ routes that define the movements in the road network. While these are highly important for an automated distribution service, human drivers might divert from these proposed routes.

When looking at the business process in Fig. 6, one starting point is an incoming shipment from an upstream operator. The **Delivery process** (in blue) describes how deliveries are managed by the (reactive) digital twin. First, one or multiple incoming shipments are announced by the upstream operators through the Shipment API and monitored by the *Data Ingestion System* to keep the digital twin updated. The existing data can be stored by the *Storage System*. Every five minutes, the *Context Entity Manager* can check whether new shipments have been announced. If this is the case, new instances of the VRP model are configured and started by the *Model Management System*. Note that in the current case, multiple alternative scenarios are created by obtaining a distance-minimizing solution and one that minimizes delivery delays for the goods that were assigned a desired delivery time. Based on KPIs that are calculated based on the outcomes, the *Decision System* component chooses one solution. The system can be configured flexible, for instance, such that the distance-minimizing solution is chosen as long as delays don't exceed a certain threshold. Optionally, if certain KPIs reach undesirable thresholds, a human system operator may be identified directly. In any case, the stop sequences and vehicle routes are transmitted to the vehicles via the push service. These instructions can then be implemented by the vehicles. Note that simple updates of the vehicles' locations do not trigger a new execution of the VRP model.

However, there is the **Traffic process** (in yellow) that may do so. The vehicle location information arrives frequently through the Fleet API and is stored. Given the current trajectory (for instance, during the past five minutes) of the vehicle and the current state of the Traffic model, the *Model Integration & Orchestration* can decide whether the discrepancy (or prediction quality) of the Traffic model is too low. In that case, the model is newly configured (by the MMS through its *Scenario Manager* component that stores the simulation parameters and threshold settings) and estimated, making use of the latest traffic information. This traffic information is also monitored by the VRP process, so if it changes, the VRP is solved again to provide better routes to the active vehicles. The interaction of the two processes exemplifies one of the core insights from our literature review and use case analysis: An urban digital twin is likely to operate on multiple time scales and shows a complex interplay between different model types.

Finally, there is the **Demand process** which is triggered once a day. It makes use of the stored shipment information from the past day, but also other historical records. After finishing the (potentially long-running) demand prediction model, a synthetic transport demand is obtained. It represents the potential incoming shipments for multiple days in the future. For each of the instances (for instance, for the next 30 days) the VRP model is solved to simulate the last-mile deliveries. The model is then able to detect whether a (near) breakdown of the system is expected for a particular day in the future. If this is the case, the human staff of the UCC is informed, through the *Context Entity Manager* API that can push updates to the digital twin data model, to take relevant measures such adding more vehicles to the fleet or renting individual vehicles for the particular days when difficulties are expected. This last part of our use case example shows how our digital twin architecture is able to cover varying model types on the spectrum between reactive and predictive applications.

6. Discussion

In this work, we extended the state of the art with a generic framework for introducing digital twin applications for city logistics. We demonstrate in a generic business process how cities can leverage this framework to create value case scenarios by using their specific models. For this, a generic model library that contains a set of models, when combined, allow the user to model different value cases, according to their needs. This fills the lack of frameworks for model orchestration, data transformation and merging that enables the bi-directional exchange of physical and virtual data that compromises the adoption of digital twin technology for cities.

Through the use of a monitoring task, model integration and orchestration, the proposed approach can handle longer feedback loops (due to predictive models) that depend on the interaction of multiple independent agents, and potentially computationally intensive modeling pipelines that predict many aspects of the urban system over a rather long-term horizon.

As discussed in Section 4.4, the ongoing implementation involves several technologies and techniques that might represent some barriers that regard the utilization of the conceptual framework. This can be the acceptance (effort and expected benefits) or how the stakeholders will see the integration and compatibility efforts with other sub-systems of a decision support tool. In the bigger picture, the referred solution building blocks in this architecture exist in the market and can provide the necessary functionality, parameters and security aspects for the implementation of the framework. This does not mean that other alternatives could not provide a better performance, but the elements described here provide complete and mature solutions for the objectives of the proposed digital twin.

With respect of the limitations of this work, some requirements such as the integration with specific systems, network optimization or cybersecurity issues (due for instance to the growth of the attack surface (Hearn & Rix, 2019)) are not considered at this level of detail. However, with regard to security and access control (through identity management) and secure data (thanks to the usage of the HTTPS protocol) the current framework already considers some of those constraints.

7. Conclusion

In this fast-changing environment, urban planners, business stakeholders, and city administrators need to be equipped with appropriate tools to conduct reliable and comprehensive analyses of upcoming business model innovations, technological changes and the changes these innovations will produce. In urban logistics, digital twins are starting to gain traction for its extensive role in supporting experimentation in urban logistics planning and policy development. However, the lack of digital twin framework for urban logistics enabling simulation model orchestrations, data transformation and merging that connect the exchange of physical and virtual data can compromise the adoption of digital twin technology for cities, which increasingly need to address city logistics problems with advanced data-driven solutions. Moreover, urban freight planning has different decision time horizons and is affected by multiple agents, that interact and are independent of each other, adding to the overall complexity of the system to be twinned.

To address these gaps, in this paper the authors present a first comprehensive platform architecture for using this data to inform individual, data-driven, and defensible policy-making in this field. To further demonstrate steps from the conceptual level to practical implementation, technical tools and implementation insights have been suggested. Moreover, real-world use cases of such framework have been presented demonstrating the capability of our framework to use bi-directional data flows and cope with different planning horizons. Through our detailed analysis of the many components needed to implement an adaptable and comprehensive framework, we intend to bring focus on the different possibilities of design architecture of DTs. Since current solutions are either highly individualized or academic oriented, cities would benefit with a more standarized and formal framework that can be deployed in a more standarized and formal way.

CRediT authorship contribution statement

Abdelhadi Belfadel: Conceptualization, Methodology, Writing – original draft, Investigation, Visualization, Validation. **Sebastian Hörl:** Conceptualization, Methodology, Writing – original draft, Investigation, Visualization, Validation. **Rodrigo Javier Tapia:** Conceptualization, Methodology, Writing – original draft, Investigation, Visualization, Validation. **Dimitra Politaki:** Conceptualization, Methodology, Writing – original draft, Investigation, Visualization, Validation. **Ibad Kureshi:** Conceptualization, Writing – review & editing. **Lorant Tavasszy:** Funding acquisition, Supervision, Conceptualization, Writing – review & editing. **Jakob Puchinger:** Funding acquisition, Supervision, Conceptualization, Writing – review & editing.

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