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Smart City Logistics Enabled by Digital Twins and Semantic Technologies

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Abstract. This research explores sustainable city logistics, emphasizing the hurdles associated with scarce urban resources, including their under- and mis-utilization due to a lack of real-time information on the available infrastructure and intense competition between companies. To face these challenges, there is a crucial need to improve the visibility of urban resources and logistics assets, as an enabler of effective and efficient resource allocation and orchestration of resource utilization and logistics operations. The advent of Smart Cities provides innovation opportunities, leading to the concept of Smart City Logistics (SCL). SCL will offer dual benefits: firstly, it improves resource visibility by profiting from the various fundamental technologies of Smart Cities, i.e., IoT and ICT, to collect and transfer the data of the ever-changing state of resources. Second, enhanced by Digital Twins, the real-time objects' states can be synchronized and mirrored, which will support the decision-making in SCL to guide the allocation of urban resources to provide energy-efficient, cost-effective logistics services dynamically and responsively. This research primarily focuses on SCL's conceptualization and modeling, while discussing potential future advancements.

Keywords: City Logistics, Smart Cities, Digital Twin, Semantics, Multimodality, Sustainability, Micro-hubs, Crowdsourcing.

1 Introduction

The importance of City Logistics is evident when considering the significant cost involved – the global expenditure was estimated to be up to 80 billion USD in 2016 [1]. City Logistics was thrust into prominence during the COVID-19 pandemic and its subsequent lockdowns, proving indispensable to society. In the post-pandemic era, consumers have rapidly adopted online shopping and home food delivery, leading to a

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considerable increase in logistics demands. In New York City, the daily parcel delivery requirement is nearly 2.4 million, with the demand for food delivery more than doubling [2]. However, urban resources have often been misused or underused in city logistics operations. Illegal behaviors like double-parking for delivery have misused these limited resources and endanger other road users. Additionally, resources are typically underutilized during off-peak hours. A study highlights that during off-peak hours, parking demand is only one-third of peak demand in Manhattan [3]. For this reason, some researchers also suggest off-hour delivery to alleviate the impacts of city logistics. Schachenhofer et al. categorized the underused urban resources, named sleeping assets, for mobilization in the logistics service innovation. Such assets comprehend neglected routes, idle real estate, and other underused resources [4].

Addressing the challenges highlighted earlier requires advancing on two significant fronts. The first involves enhancing the visibility of urban resources to accurately represent both supply and demand. This not only implies the visibility of urban and logistics resources but also calls for a clear understanding of their connections and interdependencies [5]. As a response to this challenge, logistics digitalization as well as the Smart Cities paradigm provide innovative solutions via technologies such as the Internet of Things (IoT) and Information Communication Technologies (ICT), which capture and transmit real-time states through a network of devices, thereby enhancing the visibility of their states and interconnections. The second crucial move involves the efficient organization of logistics operations based on the real-time states of urban resources. This is where Digital Twin (DT) technology comes into play, offering virtual representations of physical entities that encapsulate changes in their states and map their interrelationships. This technology lays the groundwork for effective matching of real-time supply and demand. Zhao et al. demonstrated this by utilizing DT to mirror the spatial-temporal values of resources in intralogistics, thus facilitating resource allocation decisions [6]. This application of DT can be extended to city logistics by matching delivery tasks and available urban and logistics resources. To accomplish these steps and pave the path toward Smart City Logistics, we propose the following research questions:

RQ 1: How to innovate logistics services by leveraging underused urban resources in the context of Smart Cities? The focus of this question is to design use cases and technological solutions with profit from enabling technologies of Smart Cities for efficient logistics operations while mobilizing sleeping assets to realize sustainable city logistics.

RQ 2: What methods can be used to efficiently and effectively manage and allocate urban and logistics resources, to provide responsive support to dynamic logistics demands? It aims to use timely available urban resources to achieve efficient logistics operations.

This work aims to make two main contributions to the related research area. First, it uses a real-life DT platform and use cases to showcase how DTs and semantic technologies can practically help operations management in city logistics. This is still rare in the literature of city logistics. Second, it investigates the opportunities to design

dynamic last-mile delivery schemes to improve sustainability, contrasted to the current research foci on static networks and delivery services.

The following section provides a comprehensive literature review covering Smart City Logistics, relevant technologies, and logistics organization schemes. Section 3 discusses the conceptualization and modeling of SCL, and presents preliminary results. Section 4 explores potential steps toward the practical implementation of SCL. Finally, the last section concludes this work.

2 Related works

2.1 Smart City Logistics

Smart City Logistics (SCL) is a rising concept in city logistics based on the Smart Cities paradigm. For the sake of consistency, this work defines SCL as *an integrated system of city logistics demands, assets, and resources, supported by various technologies that can monitor and synchronize the dynamic states of the objects involved in urban freight transport, aiming to make decisions automatically based on the spatial and temporal status of the assets and resources*. The definition implies that SCL is to interconnect and integrate objects related to logistics city-wide, to benefit from various technologies for efficient and effective operations management.

System digitalization and *data analytics* are the two crucial technological research streams for SCL. First of all, SCL requires digitalization on both sides of the delivery environment (the city) and key players (shippers, Logistics Service Providers, and customers). The digitalization of the delivery environment can essentially rely on the Smart Cities context, see the framework for sustainable urban logistics in the work of Pan et al. [7]. The digitalization of logistics systems has been a hot research topic for years. Most works attempt to apply IoT solutions to collect data to manage logistics operations, such as IoT-based crowdsourcing for on-demand food delivery [8]. As for data analytics, Taniguchi et al. were among the first who suggested analyzing the collected data of movements of freight and vehicles with innovative technologies, including Big Data and Artificial Intelligence, aiming at improving the efficiency and sustainability of urban transport systems [9].

2.2 Digital Twin and Semantic technology

There is no unified definition of Digital Twin (DT). Based on the various definitions clustered in the work of Semeraro et al., DT aims at mirroring and synchronizing the real-time states of its physical counterpart while being capable of prescribing the reacting behaviors through simulations [10]. From this perspective, DT will function properly with the assistance of IoT technology to capture real-time sensing data of the objects, along with the simulation models to derive solutions. The value of digital twins can not only be created from the multiple lifecycle phases of individual digital twins but also from the connection between various twins [11]. These connections can be built with the help of semantic technologies because multiple heterogeneous stake-

holders will be involved and interoperability will be a big issue. With their enhancement, full-fledged DTs can be built with unambiguous meaning for integration and interoperation. It is highly valuable to improve city logistics' overall performance with the involvement of multiple heterogeneous stakeholders.

2.3 Multi-echelon network in last-mile delivery

There are mainly two research streams in the field of multi-echelon networks in last-mile delivery. One is the Vehicle Routing Problem (VRP), and another is the Location-Routing Problem (LRP), which combines location planning with routing of the selected locations. A most researched VRP variant is two-echelon VRP, determining the routes to deliver goods to the intermediate facilities, such as satellite or micro-hubs, then shifting to another modality to deliver the final 50 feet. For instance, Zhang et al. simulate the two different modalities in the second echelon, i.e., cargo bike and parcel lockers, concluding that both scenarios save the vehicle traveling distance and operating time while using a cargo bike requires fewer vehicles to supply goods and parcel locker resulting in fewer vehicle tours [12]. Regarding the LRP, one possible scheme is to select transiting points and these points are static as the starting point to the next echelon [13]. Another one is dynamic transiting points for the transshipment, named a variable-echelon network by Bayliss et al. [14]. There is very little research focused on this type of network, one of the reasons is that most facilities are rented or owned by private logistics companies that cannot easily change in the short term. However, with the prosperity of the sharing economy and the advancement of the Smart Cities paradigm, the accessible infrastructure and the available shared facilities of LSPs can be timely informed, which makes the multi-modal network more dynamic and flexible.

This work conceptualizes the SCL by connecting objects' DTs in the context of Smart Cities. Semantic technologies will be used to enhance the interoperability and openness of this system, which can enable the communication and interaction of sub-systems (objects) in such a complex system as SCL. Moreover, variable-echelon networks will be considered in this work, with the involvement of multiple up-and-coming modalities, such as delivery robots, e-cargo bikes, and so on. The following section will detailly illustrate the modeling processes and the interaction between the digital twin platform and logistics demand for decision-making.

3 Smart City Logistics Conceptualization

3.1 Introduction

The adoption of a multi-echelon network in SCL presents two significant advantages: reduced transportation costs and compliance with strict inner-city regulations. Employing larger vehicles for freight consolidation during transportation proves to be cost-effective. However, their access to city centers is often restricted by stringent freight regulations, such as low or zero-emission zones and elevated standards for

vehicle types. Hence, it is necessary to perform transshipment to lighter and greener means near the dense or restricted area, to provide more flexible and agile delivery methods to satisfy the freight policies. These include options such as Light-Duty Vehicles (LDVs), electric cargo bikes, on-foot porters, delivery robots, and other innovative solutions.

A “Smart” urban delivery environment of SCL is crucial to handle the high dynamics and complexity, i.e., the time-changing capacities of logistics assets, availability of infrastructure, and the dynamic participation of crowd-shippers. Additionally, the implementation of multi-modalities calls for better orchestration between logistics activities and the available infrastructure. It includes larger vehicles, lighter modalities, and transshipment points. Therefore, it is necessary to model the sophisticated relationships between these objects for an efficient and effective operational organization.

Two primary outcomes are anticipated from the implementation of the SCL scheme. First, it allows for the dynamic selection of transshipment points, thereby facilitating the synchronization of the different delivery modalities, to profit from lower transportation costs of larger vehicles while satisfying the strict regulations. Second, by providing users with real-time availability of urban resources, this scheme encourages more precise and timely utilization of resources. As a result, accurate usage time helps in optimizing resource allocation, thereby enhancing resource use efficiency and reducing waste.

3.2 Key Components

3.2.1 Ontology modeling

Ontology is an essential part of semantic technologies, providing standard vocabularies to describe the domain of interest, including *classes* to define the targeted categories, *data properties* to depict attributes of various classes, and *object properties* to describe the relationship between classes. Ontology modeling will be implemented as the first step to enhance the capability of integration and interoperation of the SCL system. More specifically, ontology modeling aims to involve knowledge about the delivery environment to improve delivery efficiency and urban resource utilization efficiency. For example, as reported by the Institute of Engineering and Technology [15], vertical deliveries account for 23% of total deliveries. Kim et al. reveal that the total time spent on office building delivery is 20 minutes, from entering to exiting the building [16]. This type of moving is non-value added but worth to be improved for the efficient final-50-feet delivery. Hence, the knowledge about the final destinations should be integrated into the decision systems to assist (novice) deliverymen in the final 50 feet. The table below elucidates the process of aligning specific delivery requirements (e.g., vertical delivery) for various destination types with the attributes of multiple transportation modes. This ensures the appropriate selection of final-50-feet modalities while taking into account compatible and available transshipment points.

Table 1. Optimal modality selection and transshipment points in final 50 feet.

Final-50-feet modality	Characteristics of modalities			Applicable destination type	Transshipment	
	Capacity	Range	Vertical delivery		Transshipment Point (TP)	TP function
On-foot porter (crowdsourced)	Small	Short	Yes	OB/CA	Parking	Transshipping
Delivery robot	Medium	Medium	No	RN	Charging station	Transshipping
E-Cargo Bike	Large	Long	No	RN	Micro-hub	Cross-docking
Driver being courier	Small	Short	Yes	OB/CA/RN	-	-

Note: Office Building (OB), Commercial Area (CA), Residential Neighborhood (RN)

Fig. 1 displays the ontology model of the conceptualized SCL, including all classes, data properties, and object properties. This work considers different classes of objects in SCL scenarios. *Logistics demand* indicates the small parcels to be delivered to individual customers. Varied types of *destinations* require different *final-50-feet modalities*, referring to the transportation means to perform the delivery from the transshipment points to final destinations, as responses to the traits of the delivery tasks. *Transshipment points* include micro-hubs for modal shifting to cargo bikes, delivery spaces for on-foot porters, and charging stations for delivery robots. Two practices of micro-hubs can be provided as implementing suggestions. Firstly, the micro-hubs could be retrofitted delivery spaces, such as one pilot project in Paris in 2022¹. Another practice is locating micro-hubs in the wasteland, one example can be Collectiv Food², which sets containers (a.k.a., Points of Distribution, short as PODs) in the disused land inside the city. These practices endeavor to mobilize urban resources that are presently experiencing underutilization or complete idleness. This dynamic has the potential to catalyze subsequent innovation in logistics services, leveraging these inactive urban resources to drive transformative advancements in last-mile delivery.

Two ways to gain the information of destination type are considered here. First, importing the detailed information of an address from publicly available data sources, e.g., OpenStreetMap³. Second, defining functions of different areas. For example, La Défense in the Greater Paris area is a major business district that full of office buildings, so any address in this area can be treated as an office building. It should be noted that the office building here is an example to illustrate how to categorize the destinations concerning their characteristics and delivery requirements. The core is to integrate the knowledge of the delivery environment to effectively and dynamically support the operational decisions in the last-mile delivery.

¹ <https://www.sogaris.fr/fiche/les-micro-hubs/>

² <https://collectivfood.com/sustainability/>

³ <https://www.openstreetmap.org>

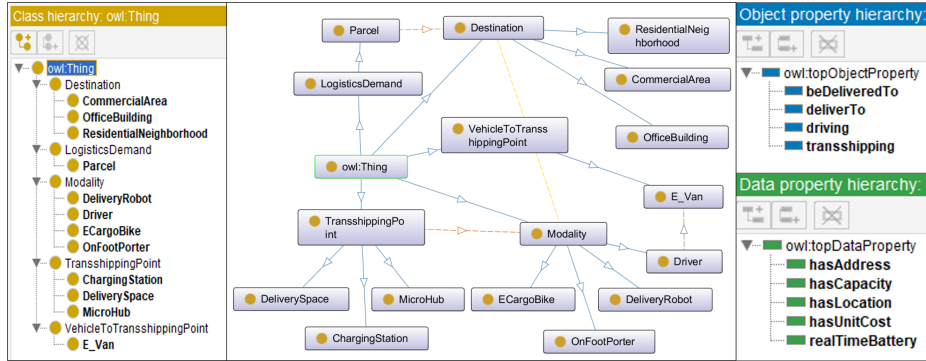


Fig. 1. Ontology model of SCL (solid lines: subclasses, dash lines: relationships).

3.2.2 Digital Twin modeling and management

Digital Twins can be regarded as both the digital representation of physical objects and instances performing as part of the ontology model. The latter role is to ensure the unambiguous description of DTs' properties and relationships for interoperability between stakeholders and further integration into smart cities. Each digital twin has a physical counterpart that performs a role in urban delivery. We assume the digital twin will synchronize the state with the physical twin via IoT devices (i.e., sensors). All DTs' states and relationships will be managed in the Thingⁱⁿ platform⁴, a multi-sided open digital twin platform supporting service innovation around Smart Cities, which is developed by Orange Innovation. As shown in Fig. 2, nodes represent digital twins, the number in the blue circle signifies the aggregated number of objects, and links indicate the relationship between two nodes. Not only the connected objects (have links) can be queried out for logistics operations, but objects' spatial-temporal values and their properties depicted in DTs can also be targeted in queries. For instance, at a given time, even though there are no connections between modality and transshipment points, based on the spatial value of one modality and its suitable transshipment points described in its DT, this type of available transshipping points within a specific distance from the modality can be queried out to support logistics operations. From this perspective, it becomes evident that the dynamic states and their properties within the DTs and established connections are pivotal in facilitating resource utilization.

⁴ <https://www.thinginthefuture.com/>

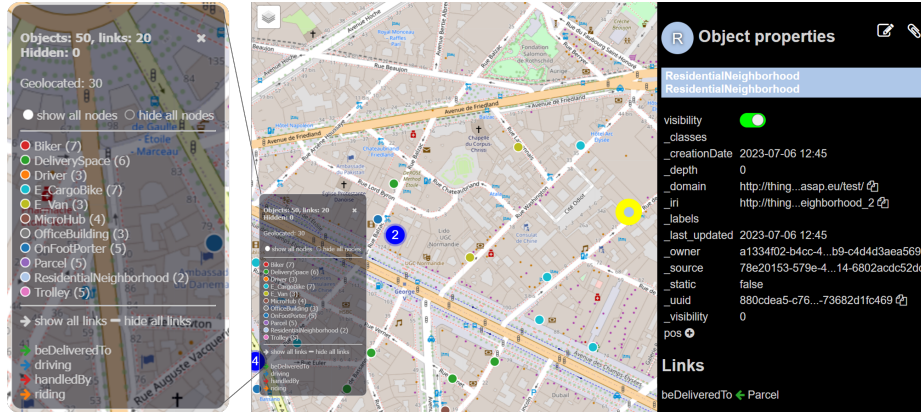


Fig. 2. Digital twins of SCL managed by the Thing'in platform.

3.3 Interaction for applications

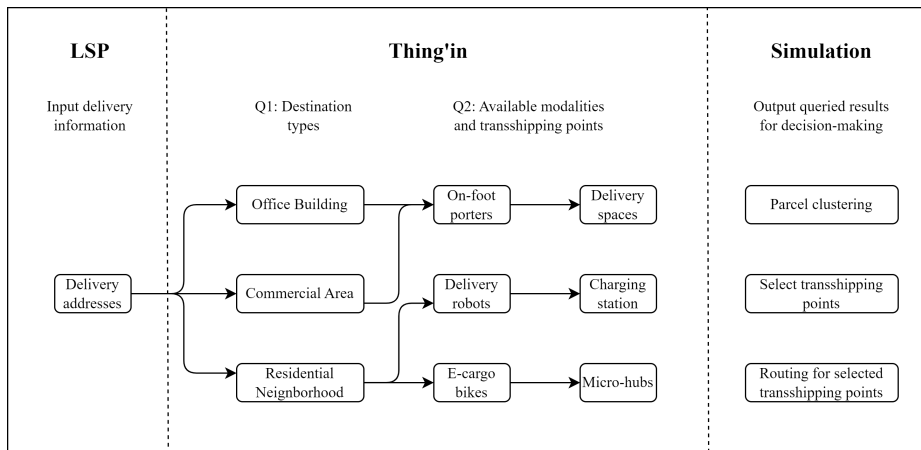


Fig. 3. Interaction processes for logistics operation decision-making.

Fig. 3 illustrates the interaction processes among the three pivotal components within the system: the DT platform Thing'in is responsible for managing knowledge and synchronized dynamic states of DTs, simulation tools assessing performance and deriving solutions by leveraging queried information from the DT platform, and LSPs, involved in inputting delivery information and executing informed decisions. This resource utilization guided by dynamic state synchronization and solutions derived from simulation would help to enhance the operation planning, which will also positively impact the environment and society. If the route planning is not been done one day before but instead of considering the actual traffic situation, accessibility of the roads, and the availability of parking, the whole tour can be cut into many more

pieces to be planned just before the operations regarding the timely resource states, which also means the predicted time slot to use these resources could be more accurate and result in reducing wastes. More specifically, under the proposed SCL operation scheme, the ‘last-minute booking’ in city logistics could be provided [17]. As a result, improving the freight parking turnover rate, enabling parking allocation when vehicles approach, mitigating the double parking so to its negative social and environmental externalities, and reducing parking cruising behavior to improve operation efficiency. All these crucial aspects could be treated as Key Performance Indicators (KPIs) and assessed in the simulation.

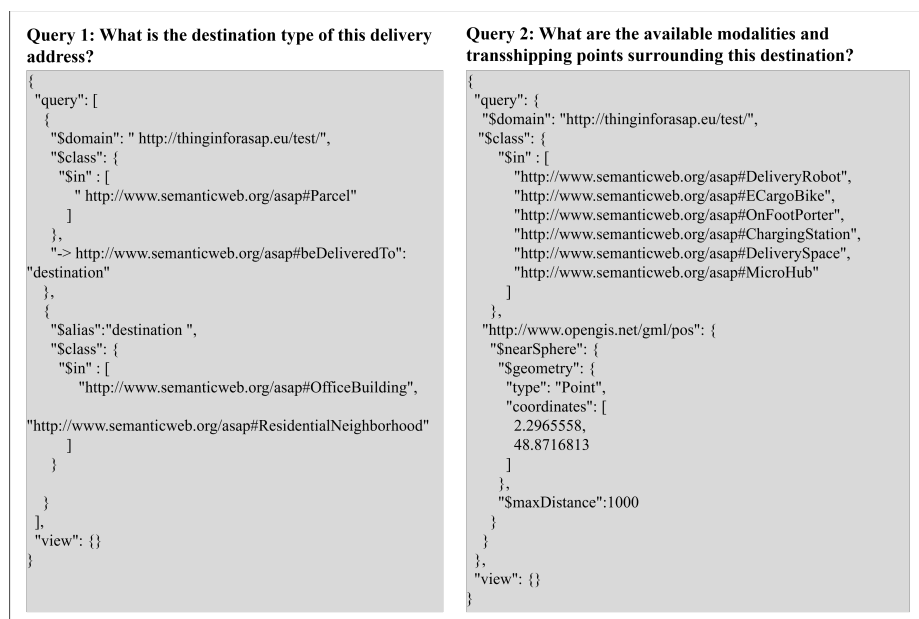


Fig. 4. Illustration of queries performed in the Thing’in platform.

The first query targets the information on destination type, which is beneficial to finding more efficient and effective modalities regarding the characteristics of destinations, as shown in Fig. 4. The second query aims at finding out the available modalities and transshipment points based on destination types. Each modality will announce a reasonable catchment area, for example, 250 meters for on-foot porters based on the experience from industrial practices. If the catchment area of one available modality covers the destinations and available transshipment points, all these supporting resources would be queried for operational decision-making.

Based on the query outputs, namely destination type, available modalities, and transshipment points, three decisions will be made. First, clustering parcels based on their density and destination type, considering the modalities’ and TPs’ capacity as constraints. Then simulating the performance of multiple combinations for evaluation

and making the second decision, i.e., selecting the best-performing modality and transiting points. These two decisions are not been made one day in advance but just before the operation. Hence, the last decision is routing for the selected next-visiting transshipment points, to transfer clustered parcels and navigate the delivery to the final destinations.

4 Conclusion

This research discussed how to improve the visibility of the urban resources in Smart Cities, and how to organize logistics activities based on the real-time urban resources states, which will pave the way toward Smart City Logistics. This work aims to provide several novelties to the related literature. First, provide responsive and efficient logistics services by using urban resources with the assistance of timely resource state synchronization and dynamic operation planning. Second, suggest smart city logistics schemes with the prosperity of Smart Cities and the prospective advancement of urban infrastructure to inspire further logistics service innovation. Third, provide the heterogeneous stakeholders with innovative digital solutions like semantic technologies, to enhance digital interoperability for collaboration. Further, showcases the perspectives of DT technologies in real practices of city logistics, and solutions to digitalize operations management. The next step is to validate the feasibility of the conceptualized scenario by modeling a large-scale case and performing interactions to support decision-making.

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