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Cognitive Smart City Logistics : a new approach for sustainable last mile in the era of digitization

Yu Liu

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THÈSE DE DOCTORAT
DE L'UNIVERSITÉ PSL

Préparée à Mines Paris-PSL

Cognitive Smart City Logistics: a new approach for sustainable last mile in the era of digitization

Logistique Urbaine Cognitive et Intelligente: une nouvelle approche pour un dernier kilomètre durable à l'ère de la numérisation

Soutenue par

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Table of abbreviations

CDT: Cognitive Digital Twin

CSCL: Cognitive Smart City Logistics

CPS: Cyber-Physical System

CPLS: Cyber-Physical Logistics System

DT: Digital Twin

ETA: Estimated Time of Arrival

GD: Graph Database

HMI: Human Machine Interaction

IoT: Internet of Things

IoV: Internet of Vehicles

ICT: Information and Communications Technology

ITS: Intelligent Transportation System

ICL: Interconnected City Logistics

JDS: Joint Delivery System

KB: Knowledge Base

KG: Knowledge Graph

LSP: Logistics Service Provider

LSCM: Logistics Supply Chain Management

LEZ: Low Emission Zone

MAS: Multi-Agent System

OWL: Web Ontology Language

OSM: OpenStreetMap

PG: Property Graph

PI: Physical Internet

SC: Smart City

SoS: System of Systems

SLR: Systematic Literature Review

TRL: Technology Readiness Level

TMS: Transport Management System

UFT: Urban Freight Transport

UCC: Urban Consolidation Center

V2X: Vehicle-to-everything

W3C: World Wide Web Consortium

WoT: Web of Things

5PL: Fifth-Party Logistics

ABSTRACT

City logistics, also named last-mile delivery herein, aims to efficiently and effectively transport goods from the distribution hub to the final destination efficiently and effectively to satisfy consumer demands in urban areas. Its significance is notable since it plays as the last leg of the supply chain and accounts for more than 20% of the overall cost. It was prominent to supply goods and food during the COVID-19 outbreak, especially during the lockdown. Thus, it has become increasingly essential in the eyes of the government and the public. Also, its importance is manifested in negative externalities toward urban sustainability, such as traffic congestion, road safety, noise, and air pollution. Hence, many cities, especially megacities with dense populations, have imposed stricter urban freight regulations to make cities more sustainable and livable. It is not a matter for one party to implement the policies. They need other stakeholders' engagement and further obtain feedback from their behavior changes to evaluate the policy's effectiveness. Logistics Service Provider (LSP), one key stakeholder, must operate in an increasingly difficult and complex environment while meeting the policies. The complexity of their operations management comes from the highly segmented freight flows and dynamic availability of logistics-supported urban resources. Therefore, they need to gain the time-changing states of urban resources to support their operations planning in such a dynamic environment.

Under the above research background, this thesis studies a digital solution in the Smart Cities context, where the objects and data are connected via IoT/ICT technologies. More specifically, we investigate Cognitive Digital Twins, Digital Twins (DT) with augmented semantic capabilities. And how they can enhance the real-time knowledge of city-wide logistics demands and resources to optimize operations planning and resource allocation. A four-layer architecture framework is developed to integrate individual logistics objects and systems into Smart Cities at a semantic level. The underlying enabling technologies and standards are, for example, Property Graph, Web Ontology Language (OWL), Knowledge Graph, and Web of Things (WoT). Then, a use case study of parcel delivery in Paris is conducted upon a real-life DT platform called Thing in the future (Thing'in), coupled with an

agent-based simulation on AnyLogic to demonstrate a real-world application of our approach. The results imply that when individual DT, owned by one stakeholder of city logistics, is capable of communicating with the dynamic environment, it can improve logistics efficiency while facilitating policy evaluation. It will result in fewer negative externalities, better utilization of resources, and provide insights for city municipalities to improve policy-making. Our work also showcases the potential of offering new business services to logistics service providers. Based on our work, an actual app prototype is developed by our partner to aid driving and walking delivery, showing our work's concrete applicability.

RÉSUMÉ

La logistique urbaine, également appelée ici livraison du dernier kilomètre, vise à transporter de manière efficace et efficiente les marchandises depuis le centre de distribution jusqu'à la destination finale afin de satisfaire les demandes des consommateurs dans les zones urbaines. Son importance est notable puisqu'elle joue le rôle de dernier maillon de la chaîne d'approvisionnement et représente plus de 20 % du coût global. Il a joué un rôle important dans l'approvisionnement en marchandises et en nourriture lors de l'épidémie de COVID-19, en particulier pendant le confinement. Elle est donc devenue de plus en plus essentielle aux yeux du gouvernement et du public. De plus, son importance se manifeste par des externalités négatives pour la durabilité urbaine, telles que la congestion du trafic, la sécurité routière, le bruit et la pollution de l'air. C'est pourquoi de nombreuses villes, en particulier les mégapoles à forte densité de population, ont imposé des réglementations plus strictes en matière de fret urbain afin de rendre les villes plus durables et plus vivables. La mise en œuvre de ces politiques n'est pas l'affaire d'une seule partie. Elles ont besoin de l'engagement d'autres parties prenantes et d'obtenir un retour d'information sur leurs changements de comportement pour évaluer l'efficacité de la politique. Les prestataires de services logistiques (PSL), l'une des principales parties prenantes, doivent opérer dans un environnement de plus en plus difficile et complexe tout en respectant les politiques. La complexité de la gestion de leurs opérations provient de la forte segmentation des flux de marchandises et de la disponibilité dynamique des ressources urbaines soutenues par la logistique. Par conséquent, ils doivent acquérir les états changeants des ressources urbaines pour soutenir la planification de leurs opérations dans un tel environnement dynamique.

Dans le contexte de recherche ci-dessus, cette thèse étudie une solution numérique dans le contexte des villes intelligentes, où les objets et les données sont connectés via les technologies IoT/ICT. Plus précisément, nous étudions les jumeaux numériques cognitifs, les jumeaux numériques (DT) avec des capacités sémantiques accrues. Et comment ils peuvent améliorer la connaissance en temps réel des demandes et des ressources logistiques à l'échelle de la ville pour optimiser la planification des opérations et l'allocation des ressources. Un cadre d'architecture à quatre couches est développé pour intégrer les objets et systèmes

logistiques individuels dans les villes intelligentes à un niveau sémantique. Les technologies et normes sous-jacentes sont, par exemple, Property Graph, Web Ontology Language (OWL), Knowledge Graph et Web of Things (WoT). Ensuite, une étude de cas d'utilisation de la livraison de colis à Paris est menée sur une plateforme DT réelle appelée « Thing in the future » (Thing'in), couplée à une simulation à base d'agents sur AnyLogic pour démontrer une application réelle de notre approche. Les résultats impliquent que lorsque la DT individuelle, détenue par un acteur de la logistique urbaine, est capable de communiquer avec l'environnement dynamique, elle peut améliorer l'efficacité de la logistique tout en facilitant l'évaluation des politiques. Il en résultera moins d'externalités négatives, une meilleure utilisation des ressources et une meilleure compréhension des municipalités pour améliorer l'élaboration des politiques. Notre travail met également en évidence le potentiel de l'offre de nouveaux services commerciaux aux prestataires de services logistiques. Sur la base de nos travaux, un prototype d'application réelle est développé par notre partenaire pour faciliter la livraison en voiture et à pied, ce qui montre l'applicabilité concrète de nos travaux.

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CHAPTER 1 General introduction

1.1 Research context

City Logistics is concerned with urban freight transportation and is aimed at sustainability and livability while managing the inbound, outbound, and inner freight movement. While it provides essential services to citizens, it has not only resulted in operational costs but also caused other external costs, like noise pollution, air pollution, congestion, accidents, etc. (European Commission 2019a). Besides, following the trend of urbanization reported by the United Nations in 2018¹, there will be 43 mega-cities by 2030, with each being home to more than ten million inhabitants and the projected growth of the world's urban population to 68% by 2050. Another recent trend is the new paradigm of 15-minute cities, which “implies having all necessary amenities within a short walk, bike ride, or public transit trip from one's home.”² Either way, it is plausible that city logistics will play a crucial role in urbanization as well as the livability of a city. More notably, urban areas cover only 0.4-0.9% of the global land surfaces, where more than half of the world's population dwells and are responsible for around three-quarters of global final energy use and related carbon dioxide (CO₂) emissions (Marvuglia et al. 2020).

With the steep urbanization rate, there is an unavoidable contradiction between resource scarcity and growing demands for goods delivery and logistics services by this surging population in urban areas. For this reason, city logistics is proposed to be studied as a complex system to arrive at sustainable operations and efficient urban resource utilization. Specifically, the urban resources here refer to the labor, infrastructure, or urban land for logistics purposes, like couriers, parkings, road networks, (un)loading space, etc. As a complex system, city logistics is composed of heterogenous stakeholders, which means they operate individually and separately with a lack of holistic cooperation in most cases. The main city logistics stakeholders include shippers, Logistics Service Providers (LSPs), consumers, and city administrations, representing the private and public sectors.

¹ <https://www.un.org/development/desa/publications/graphic/world-urbanization-prospects-2018-more-megacities-in-the-future>

² <https://www.weforum.org/agenda/2022/03/15-minute-city-stickiness/>

For LSPs, they face various challenges from operations management. For example, they need to deal with highly fragmented freight flows. It results from multiple typologies of flows, such as e-commerce or food delivery; speedy requirements, like same-day, on-demand, or instant delivery; and delivery options such as home delivery, parcel lockers, and pickup points. The omnichannel marketing strategy has much intensified such flow fragmentation (Verhoef, Kannan, and Inman 2015). Thus, optimizing the efficiency of such freight flows is extremely demanding while satisfying the operational constraints and customer service level.

Additionally, it is hard for LSPs to gain the time-changing availability and accessibility of logistics-related resources to support the high dynamics of urban logistics demands. Because the city administration charges urban infrastructure and the two parties are rarely connected, it generates many efficiencies and sustainability issues. For example, one research done in Seattle shows that the total cruising time of commercial vehicles to find available parkings in downtown is more than one hour, accounting for 28% of the whole trip time (Dalla Chiara and Goodchild 2020).

Regarding the collaboration between stakeholders (particularly LSPs and city administration), one obstacle is the lack of seamless and effective information sharing for a holistic vision of the city-wide delivery environment. As a result, each of them tries to perform optimization from their own view to make the most of the urban resources. But this independent and individual planning without real-time information sharing and cooperation will inevitably cause resource waste. Hence, it is crucial to keep various stakeholders informed of the dynamic operational events of each other. In this case, they can communicate their logistics demands, and city municipalities can involve in urban resource allocation from a city-wide perspective (Gatta et al. 2019; Stathopoulos, Valeri, and Marcucci 2012). To achieve this goal, it calls for effective and efficient solutions for the interconnection and integration of heterogeneous stakeholders at the information and operations level.

These solutions were proposed to increase understanding of dynamics and uncertainty in operations management. As an example of a well-established solution, RFID (Radio-Frequency Identification) was used to locate and track inventory, assets, and goods in the workflow to improve supply chain visibility. Real-time information could be shared through

the supply chain for better operations management. It has become more popular as RFID becomes more cost-efficient, which is the same reason for the rapid development of other sensing technologies. Therefore, more smart sensors and embedding devices have been used to capture and share objects' data, so a network of connected devices was generated, namely the *Internet of Things (IoT)*. After tons of objects' data are generated from the physical world, IoT applications and platforms are sprouting to process data, extract value by data analytics from descriptive, diagnostic, predictive, and prescriptive views to generate insights to assist operations management.

Although object-level visibility is more advanced than years ago, two gaps are still shown. One is the fragmentation among IoT applications, which means one specific application can only control a group of objects, resulting in these IoT-enhanced objects not being accessed and used apart from the related application. For this reason, the *Web of Things (WoT)* has emerged to integrate fragmented IoT applications through standardized web technologies to break the segmentation among objects and allow them to interact across systems³. In WoT, machine-readable and standardized objects can be identified and integrated into the Web regarding their inner relationships to direct the data processing and operations. Take one of the most common logistics scenarios as an example. A vehicle is loaded with some parcels with their depicted relationships. When vehicles' location data is updated, all parcels' position information will be renewed. And if one parcel was delivered, it will be immediately removed from the loading list of the vehicle. WoT, in this scenario, will stress the connection of objects for updating objects' status. From this aspect, Digital Twin (DT) technology performs very well in bi-directional synchronization of the logistics dynamic demands and the time-changing resource availability and in horizontal interaction with other DTs to support operations planning.

Till now, rich research works have been done to enhance the collaboration between city administrations and LSPs and between LSPs at the data level. For example, Open Data means the data can be fully accessed and exploited by the public, which supports stimulating service innovation and knowledge propagation. The increasing deployment of Open Data city-wide

³ <https://www.w3.org/WoT/>

or nationwide shows its importance and growing attention, such as Paris Open Data and open mobility data in German⁴. Besides, with the advancement of Information and Communications Technology (ICT), information was shared between supply chain partners to enable cooperation and coordination to improve overall efficiency and performance. However, either data sharing or information sharing, two steps are essential to make it happen and generate benefits. The first step is data or information consolidation and sharing. It requires digital interoperability, which aims to achieve quick, seamless, secure, and reliable data and information exchange to enhance the cooperation or competition of independent logistics parties (Pan et al. 2021). The second step is the creation and co-creation of value. Following the 5C architecture to implement Cyber-Physical System (CPS) (Lee, Bagheri, and Kao 2015), as shown in Figure 1. Data and information must be translated into knowledge to guide decision-making or behavioral reactions. In response to these two keys, semantic technologies, which aim at processing data in a machine-understandable way and support data sharing with unambiguous meaning, are advanced and promising to provide interoperability and manage knowledge. More specifically, it makes the siloed data pieces interoperable and easy to integrate, based on which knowledge management and discovery can be performed across the Web or various system datasets.

Based on the existing related literature, this thesis aims to advance the research in two directions:

First, we extend the application of semantic technologies in city logistics from data to digital twins level, *viz.* semantic (and cognitive) digital twins from sustainable operations management in city logistics. The gaps mentioned above have led to the inadequacy of cooperation between LSPs or between LSPs and other stakeholders. The challenging aspects are that data and information have been stacked in heterogeneous stakeholders' silos, dynamic logistics demands, and available urban resources are fragmented. They cannot be informed of each other and be interoperated, which results in obstacles to resource sharing and cooperative planning. This thesis will contribute to the timely management of the operational dynamics and the usage of semantic technologies to provide interoperability between

⁴ <https://mobilithek.info/about>

stakeholders as well as their objects or systems. This thesis will also stress the significance of object (*viz.* digital twins) connection and connectivity for real-time decision-making, which is more efficient than the current (shared) data-driven decision-making processes. And it will be more pertinent for related knowledge description and creation, especially in the future Smart Cities context.

Second, the new paradigm Physical Internet is considered for service innovations. From the view of interconnected and interoperable logistics, Physical Internet (PI), an innovative paradigm aiming at an open global logistics network, also provides us with a motivating vision to move forward (Ballot, Montreuil, and Meller 2014). For example, one of the concrete benefits of the interoperability of PI is called *plug-and-play*, which means logistics service providers can access the network and play as parts of it and leave at any time without any influence. Hence, in this thesis, PI will be adopted as the background of research since city logistics is complementary to it and plays the final segment of this network to provide delivery services.

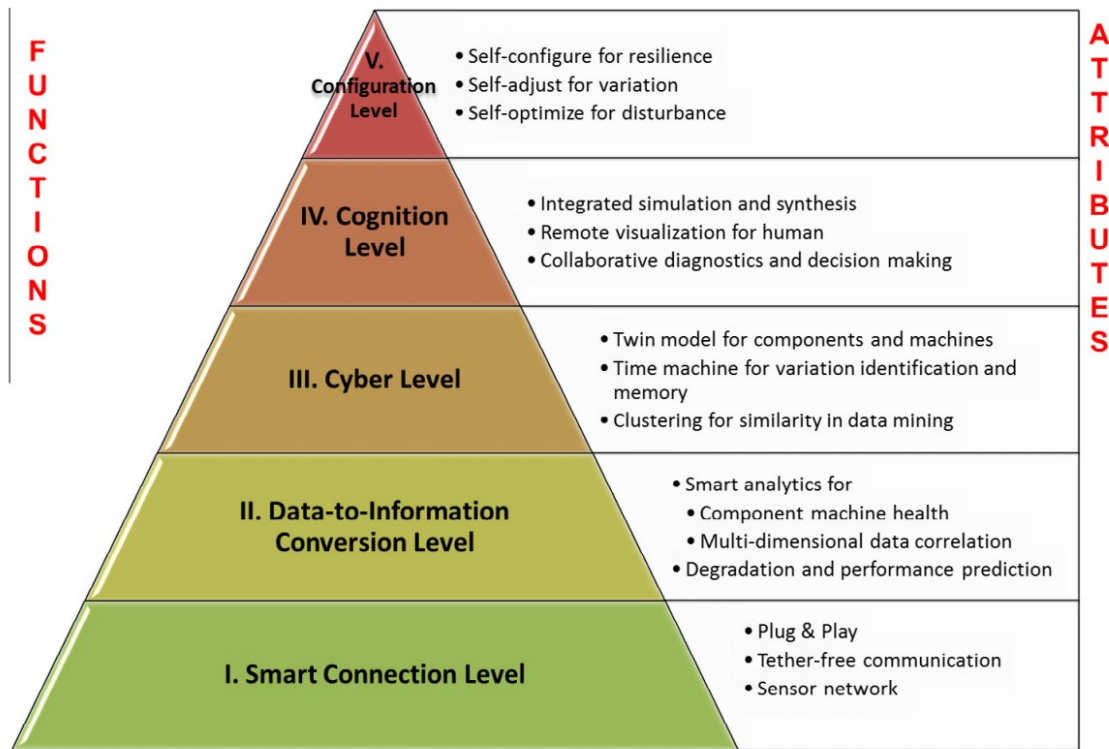


Figure 1. 5C architecture for implementing Cyber-Physical System (Lee, Bagheri, and Kao 2015).

1.2 Research questions and objectives

In this thesis, we investigate the development and application of a new concept - Cognitive Smart City Logistics (CSCL), aimed at gaining real-time knowledge of city-wide logistics demands and resources to optimize resource planning of the city and support operations management of LSPs. Semantic modeling, optimization, and agent-based simulation are employed to proof the efficiency and effectiveness of the concept. Besides, several research questions (RQs) should be addressed during the research:

RQ1: What are the state-of-the-art (SoTA) solutions for sustainable city logistics in the context of the smart city, and what are the trends and challenges? Many SoTA solutions have been identified from the literature, particularly regarding data analytics, autonomous systems, cyber-physical systems, and digital twins (DT). Based on the motivations discussed above, we then emphasized digital twins and their evolutions toward semantic and cognitive ability.

RQ2: How can DTs and semantic technologies jointly affect sustainable smart city logistics? How can they integrate with the city delivery environment and the SoTA technologies and standards for real-life applications? An architectural framework has been built upon a bottom-up modeling approach and enabling technologies and concepts to investigate the question. The concept of Cognitive Smart City Logistics (CSCL) is suggested and defined in this thesis, which aims at a holistic and real-time vision of the demands and resources of city logistics for operations management and planning.

RQ3: How can the CSCL assist in resource planning and operations management for sustainable city logistics? What are the qualitative and quantitative outputs and outcomes? Use cases with several real case datasets are investigated via optimization and simulation studies. Qualitative and quantitative results are validated and discussed to gain managerial implications and insights.

RQ4: What long-term impact can CSCL have on the current city logistics ecosystem and the key stakeholders? How would it revolute city logistics towards digitization and sustainability? An in-depth analysis and discussion will be conducted on digitalized city

logistics' current and future ecosystems, i.e., the so-called Smart City Logistics scenario.

Chapter	Research Question	Overview
CH2	RQ1: What are the state-of-the-art (SoTA) solutions for sustainable city logistics in the context of the smart city, and what are the trends and challenges?	Literature Review City Logistics (challenges, opportunities, solutions) Digital Twin (application areas, maturity, and applications)
CH3	RQ2: How can DTs and semantic technologies jointly affect sustainable smart city logistics? How can they integrate with the city delivery environment and the SoTA technologies and standards for real-life applications?	Cognitive Smart City Logistics (CSCL) Four-layer architecture framework Three crucial aspects: real-time, city-wide, knowledge
CH4		Semantic Cyber-Physical Logistics System (Layer 1 - 3) Bottom-up modelling: (Bottom) Property Graph, (Up) Ontology Implementation tools: Protégé, SPARQL, Thing'in platform
CH5	RQ3: How can the CSCL assist in resource planning and operations management for sustainable city logistics? What are the qualitative and quantitative outputs and outcomes?	Simulation-based optimization (Layer 4) Input: semantic interaction results (query results) Output: optimal operation decisions
CH6	RQ4: What long-term impact can CSCL have on the current city logistics ecosystem and the key stakeholders? How would it revolute city logistics towards digitization and sustainability?	Outputs and outcomes: application prototype Impacts: economic, environmental, social, ecosystem
CH7		Contribution and limitations Potential extensions of the research: Multi-Agent System, Knowledge Graph, Service innovation

Figure 2. The relationship between Research questions and critical points of each chapter.

Furthermore, the objectives and expected results of this research can be summarized as follows:

- (1) Investigate the research status and industrial practices of city logistics operations in the era of digitalization. Specifically, we study the sustainable city logistics operation supported by the data or information gained from logistics demands and urban resources, how they perform to enhance the operations and what research gaps are valuable for further research.

- (2) Explore the value of the overall understanding of the delivery environment by comparing it with the current studies and practices. Research the possibilities and chances to gain an understanding with the help of the current advanced technologies.
- (3) Establish the understanding with the help of the technologies provided by the investigation, and build an architecture framework to achieve the understanding from three aspects, i.e., real-time, city-wide, and at the knowledge level.
- (4) Figure out the efficient and effective interaction between logistics demands and the overall understanding of the delivery environment and the decision-making process to plan and allocate available urban resources as responses to the informed logistics demands.
- (5) Evaluate the performance of logistics activities and urban resource utilization in the CSCL concept. Moreover, generate managerial insights for various stakeholders, make a demonstration prototype to validate its business potential, discuss the influence on efficiency and sustainability, and clarify the thesis's contribution, limits, and future research perspectives.

1.3 Research methodology

In this thesis, we adopt the following research methodologies to investigate the research problem and questions discussed above.

First, we conduct a literature review of the current research on city logistics. It concludes the rising key sustainable issues and new trends of research and practices. Regarding the use of data and information to support city logistics operations, we primarily focus on where the data and information are from, what they are about, and how they are processed for value extraction. Then, we further review the literature about the importance of knowledge application in logistics decision-making and why it differs from the works in the level of data and information. From a systematic view, discuss the significance of real-time knowledge city-wide for decision-supporting. Next, investigate the advanced technologies and determine their feasibility in achieving real-time synchronization and communication, knowledge

management, and city-wide interconnection, integration, and interaction. Last but not least, Digital Twin, a promising technology in operations management, was thoroughly reviewed to explore the potential in Logistics Supply Chain Management.

Second, we conceptualize the architectural framework for developing the CSCL concept. The framework is essential to clarify the function of the technologies adopted and the system modeling and integration approach in this work. The most promising technologies and standards are deeply reviewed, and their appropriateness is analyzed before being adopted in the framework.

Third, we design use cases to validate the feasibility of the proposed framework and assess its performance in supporting operations decision-making. We selected to investigate a case of parcel last-mile delivery with a focus on commercial parking lot management, which has been identified as a severe city logistics problem of the sustainability issue. To this end, a case in Paris, based on actual practices with some real datasets (demands, parking areas), is modeled and simulated with the support of optimization and agent-based simulation models. More specifically, we follow the following these steps: conceptualizing an operational logistics scenario with logistics demands and urban resources, modeling the scenario into a delivery environment directed by the framework, performing interaction of logistics demands via a real-life DT management platform, and lastly, simulating urban resource allocation with the help of agent-based simulation software. In the last step, we cooperate with a team from Orange Innovation, a French telecommunication enterprise research lab, to develop the demonstrated prototype to evaluate the value of this work in industrial practices.

Finally, based on the qualitative and quantitative results from the case study, we discuss the perspectives of CSCL regarding its outputs and outcomes. We first discuss the managerial implications, extending the scope from the parking case to general operations management under such a concept. Further, we discuss the long-term impacts on the current ecosystems of city logistics. In particular, it is worth investigating how the presence of new stakeholders in the ecosystem will affect the value creation and transition, which are, in this case, the orchestras of data and IoT objects and their interconnections.

1.4 Structure of the thesis

The rest of the thesis will be organized as follows:

Chapter 2 investigates the research status in City Logistics and the promising technology that can mirror the operational state of urban resources. More specifically, city logistics' challenges, opportunities, and state-of-the-art solutions will be reviewed, as well as the current studies about Digital Twin in logistics, which has been regarded as a promising solution to the issues and challenges. The investigation contains its areas of application, provided services, technology maturity, and its development and chances will also be noticed.

Chapter 3 introduces the Cognitive Smart City Logistics (CSCL) and the four-layer architecture framework for implementation, including the function of each layer and the most crucial three aspects presented, namely real-time, city-wide, and knowledge. The first two layers aim to establish the Cyber-physical logistics system, synchronizing the operational status and dynamics of individual urban resources. The third layer is for semantic interoperability, enabling the interconnection and interaction for stakeholders' sharing and collaboration. The top layer is named logistics web application, which applies the operational information and shares semantics to respond to demands from the stakeholders.

Chapter 4 explains the semantic modeling procedures in freight parking management as the framework implementation from the first three layers out of four. The bottom-up modeling approach was selected because of the complexity and hard-to-gain overall understanding of the city logistics system. Digital Twin, the replica of its physical counterpart equipped with simulating capability, will be first modeled by Property Graph (PG) to show its properties and relationships and augmented with semantic ability by Web Ontology Language (OWL)-enabled ontology model. Thing'in platform, initiated by *Orange innovation*, can be used to manage the overall environment for state updating and semantic interaction.

Chapter 5 presents the simulation-based optimization as the implementation of the framework from the top layer out of four layers. It conducts simulation based on the timely objects' state and queried semantics to make decisions. For example, Freight parking as a

specific case contains two-phase decision-making. Therefore, the synchronized state and semantic query results related to the two-phase decision problems will be simulated to find the optimal solution. These two problems were expressed via mathematical modeling and solved by greedy and genetic algorithms. Until this stage, the framework feasibility has been validated by showing the differences made from obtaining dynamics from the operational environment and knowledge from the semantic interaction.

Chapter 6 discusses the impacts of this semantics-supported framework on the city logistics operation, including the effects on various stakeholders and potential city logistics applications. The eight types of DT services identified in the literature review will be discussed here to innovate the development of applications. Semantic technologies can be further extended, like knowledge discovery in Knowledge Graph (KG), to enhance city logistics operations.

Chapter 7 concludes this thesis, clarifies the limits, and discusses the extensions of the research.

CHAPTER 2 Literature review

Résumé

Dans ce chapitre, nous nous pencherons plus en détail sur les défis et les problèmes qui se posent aujourd'hui dans les opérations de logistique urbaine, et nous étudierons en outre l'état actuel de la recherche pour y faire face. Enfin, nous proposerons une solution numérique prometteuse et effectuerons une analyse documentaire spécifique dans ce domaine afin d'évaluer son potentiel dans le domaine de la logistique urbaine.

Abstract

In this chapter, we will dive into more details about challenges and issues shown in the city logistics operations today, and furthermore investigate the current research status to deal with them. Finally, we will propose a promising digital solution and conduct a specific literature review in this field to assess its potential in the city logistics field.

City logistics is a complex system. For this reason, no impacts occur separately, and the causal factors that can improve also need to be considered by the whole system. Therefore, we choose the systematic view to investigate how city logistics performs regarding society, environment, and economy. The state-of-the-art research that can support city logistics as a system will be more focused, like stakeholders' interaction effects studies or Smart City. On another side, the trend that can enhance the interconnection inside the city logistics system will also be paid more attention to, like Sharing economy. By seizing these two opportunities, city logistics can behave more as a whole system with the interconnection supported by various technologies and enhanced by sharing economy. Specifically, SC provides the technical environment to interconnect the components of the city logistics system, and the development of sharing economy increases the possibility and willingness of stakeholders to

interconnect with each other, such as the assets' owners, service providers, and customers.

The interconnection of the city logistics system can be realized with the help of Digital Twin (DT), from physical-digital connection, inner bi-directional interaction, and digital interconnection. Physical-digital connection means the physical objects can be mirrored into cyber space, where DT plays as a digital replica. Inner di-directional interaction indicates the changes and dynamics of physical objects can be transferred to DT. Similarly, the advancement of DT can also be communicated to its physical counterpart. DT can advance through the executable simulation of one or a group of DTs, where these DTs have been networked via their relationship described by ontology. For this reason, DT is crucial to take this research one step further, and an in-depth literature review is worth to be conducted.

2.1 City Logistics

2.1.1 Challenges

2.1.1.1 Urbanization

According to the United Nations (2018) prediction, the world is expected to have 43 megacities by 2030, and each of them will accommodate more than 10 million inhabitants. These megacities dwell 54% of the world's population, which is expected to go up to 68% by 2050. The urban population has increased rapidly to 4.2 billion in 2018 from only 750 million in 1950. The high urbanization rate has been shown in several top-list regions, including Northern America (82%), Latin America and the Caribbean (81%), Europe (74%), and Oceania (68%). Take an extreme example of Shanghai, China, which dwells 23 million people in an urban area, which accounts for nearly 90% of the population, and the density is 3632 persons per square kilometer (Cui and Shi 2012). Except for the mega-cities that have emerged, there are also 577 middle-weight cities with a population between 15,000 and 10 million⁵, and mega-urban regions, defined as a closely interconnected medium- or large-cities, such as Rhine-Ruhr Metropolitan Region, where lives 11.9 billion people. For these cities inhabited by such a number of people, traffic congestion is the most outranking problem because of the infrastructure overload, where the freight traffic plays as the drivers

⁵ <https://www.mckinsey.com/featured-insights/urbanization/urban-world-mapping-the-economic-power-of-cities>

and suffers simultaneously. The rapid growth of the population in urban areas results in a series of problems. One category is the *external costs* mentioned by European Commission (2019a), like air and noise pollution, traffic congestion, accidents, energy consumption, and land shortage. Another category is *opportunity cost*. Bretzke (2013) describes it as the equivalent of time lost by the traveler and vehicles paid on congested roads. Regarding urban freight transport under this serious situation, the surging amount of urban inhabitants will further exacerbate the conflict between limited urban resources and their increasing logistics needs. To tackle these issues, promising solutions are called to face these challenges.

2.1.1.2 Sustainability

Sustainability is one goal of city logistics, which aims to reduce energy consumption and Green House Gas (GHG) emissions, air pollutants, and noise pollution (Taniguchi 2015). And from a more macro view, three dimensions of performance need to be considered, i.e., people, planet, and profit⁶. city logistics' operational situation is still far from achieving a livable and health-friendly environment for citizens. For instance, another research quantified the goods movement influence, which contributed 20% to 30% of vehicle kilometers and 16% to 50% of air pollutants emissions, depending on the considered pollutant. It was caused by strategic decision-making in various regional, national, or supra-national economic sectors (Dablanc 2007). Likewise, one research in London (2015) showed that urban transport was a major contributor to NO_x and PM₁₀ emissions, accounting for 63% and 52%, respectively. So it calls for attention and action to contribute to sustainable and livable living conditions through urban planning, efficient resource utilization, policy-making, and the usage of energy-efficient vehicles.

Urban resources are scarce, so the solutions can be to make the best use of existing resources in terms of time and space or exploit or develop new resources. As for leveraging resources from the perspective of time, Off-Hour delivery can be used as an example. The New York Metropolitan area trial showed giant benefits, including travel time savings,

⁶ <http://www.ibrc.indiana.edu/ibr/2011/spring/article2.html>

service time reduction, and environmental pollution savings (Holguín-Veras et al. 2011). From the spatial view, using canals for transportation is one of the cases. One research in Amsterdam shows freight transported by canals can generate a sufficient loading rate of 82% with no delay on the delivery, which also results in congestion reduction and provides one more delivery alternative (van Duin et al. 2014). In order to exploit resources that haven't been used for logistics purposes, Awaken Sleeping Assets Projects (ASAP)⁷ is undergoing to identify the unused or underutilized urban resources for sustainable city logistics. As a new resource, the Underground Freight Transport system is called to be developed because of the congestion caused by road transportation and other negative impacts, like traffic safety, noise, and air pollution. Apart from the high investment and long realization time, the benefits could be summarized to social (reduction of urban land use, traffic safety), environmental (reduction of emissions, noise, congestion, energy-use), and economic (direct delivery, low variable cost, 7/24 service) (Visser 2018).

2.1.1.3 Heterogeneity

Heterogeneity is a vital characteristic of a complex city logistics system. It mainly comes from stakeholders, such as carriers, retailers, customers, and public administrations, as well as their various objectives, measures adopted, activities performed, and resources they possess. Stakeholders can be categorized into public and private segments, where city administrations and carriers, a.k.a. Logistics Service Providers (LSPs), are essential. Therefore, their interests and relationship significantly influence the city logistics system since it will direct their decision-making and policy-making, behavior patterns, and willingness to collaborate and cooperate. For example, from the view of the city, they expect LSPs to innovate the services that satisfy the various types of demands from retailers and customers while contributing to urban sustainability and livability. However, on the LSPs' side, service innovation is highly dependent on the subsidies and supported policies that city administrations provide since the concerns of unpredictable risks and profitability. As a result of this heterogeneity, urban policies on freight mobility showed inefficiency, and LSPs show low engagement in creating new services even though the logistics demands are rapidly growing (Dablanc 2007).

⁷ <https://jpi-urbaneurope.eu/project/asap/>

Heterogeneity exists between stakeholders and can be observed in the same group of stakeholders. For an example of LSPs, Stathopoulos et al. (2012) investigated 195 operators, showing very different policy acceptability and behavioral reactions towards the same freight policy. It means these heterogeneous operators need to be well considered to support the whole processes of urban policy-making, evaluation, and deployment. In turn, the innovative freight policy making can be improved to gain acceptance and cooperation from the LSPs to realize the social and environmental benefits the city municipalities expect.

Urban Freight Transport (UFT) needs to operate in different cities, which differ in size, economy, and political aspects. Thus, overall awareness is desperately needed to produce profits by integrating freight transport operations and local sustainable regulation. It requires a deep understanding of vehicles, goods, facilities, and infrastructure as the essential elements of the UFT system. At the same time, their close relations showed in facility accessibility (goods and facility), transport (goods and vehicle), land use (facilities and infrastructure), and traffic (vehicle and infrastructure). However, this awareness is not complete. It has obviously shown in the UFT system. In land use, the localization of logistics facilities is less considered and limited by city spatial planning without building any connection to the infrastructure. As a result of a lack the understanding of accessibility, it is hard for shippers to know how their shipment influences transport. For carriers with no access to delivery alternatives, providing high-quality service is costly and more demanding. As for transport, since the integration inside LSPs, they can realize the internal consolidation for efficiency and cost savings, but since they lack awareness of the overall UFT environment, they can't cooperate with others for external consolidation. Last, the traffic condition is deteriorating because insufficient loading spaces were provided in the city's spatial planning. LSPs use infrastructure inefficiently since they lack cooperation for goods consolidation and connection to the infrastructure to understand its accessibility (Lindholm and Behrends 2012).

2.1.2 Opportunities

2.1.2.1 Smart City

According to European Commission (2019b), Smart City provides more efficiency than traditional networks and services by using digital solutions to profit for its inhabitants and business. And using digital technologies is for better resource utilization and fewer emissions. It was described as an instrumented, interconnected, and intelligent city. Instrumented refers to sources of real-time, real-world data from physical and virtual sensors. Interconnected means integrating those data into an enterprise computing platform and communicating such information among the various city services. Intelligence indicates using multiple techniques in operational business processes to make better operational decisions, including complex analytics, modeling, optimization, and visualization (Harrison et al. 2010).

Smart city was developed through various techniques. To this end, the three basic categories are physical infrastructure, smart computing technologies, and mobile, virtual, and ubiquitous technologies (Nam and Pardo 2011). Physical infrastructure is already established and is time- and cost-consuming to change, so it prefers to be empowered by technologies to operate efficiently and effectively. For this reason, the Internet of things (IoT), which aims at connecting devices and exchanging data for service providing, is promising to converge the physical infrastructure and digital computational environment. IoT provides us with two perspectives on dealing with physical “things.” In one aspect, IoT makes the Internet even more immersive and pervasive, enabling easy access and interaction with “things.” In another aspect, it reminds us thinking the service provision by these connected things. Therefore, Zanella et al. (2014) studied the enabling technologies, protocols, and architecture of urban IoTs to support service innovation and value creation. For example, protocols are crucial in providing service to multiple stakeholders in smart city projects within a large scope. Thus this study shows the tolerable delay of the IoT data exchange, such as the lighting and parking information needing to be updated every minute, while the traffic information can tolerate five minutes to be synchronized. In this smart urban environment, data techniques are required to process tons of data and extract value from them. Hence, Rathore et al. (2018) established an IoT-based Smart City, where big data analytics was used to gain knowledge

from data to support decision-making. Datasets from smart homes, smart parkings, weather systems, and vehicle networks have been involved in experimenting and showing better decision-making capability. Besides, they have validated that Smart Transportation System (STB), as a crucial part of a Smart City can perform well in this real-time environment by responding to transport queries and traffic problems.

As to smart computing technologies, because of the enormous amount and variety of data that have been generated, it calls for excellent capabilities for handling data, like Big Data analysis and Cloud Computing. In addition, it will foster the development of several applications and platforms to provide new services to citizens, companies, and public administrations (Zanella et al. 2014). An interoperable environment is necessary to enact collaboration and communication among multiple stakeholders. For example, a Smart City digital twin architecture was suggested for semantic interoperability, where knowledge representation and reasoning work alongside machine learning formalism. It provides city stakeholders with enhanced situation awareness and decision-making support for managing urban infrastructure and services embedded in space-time terrain (Austin et al. 2020).

And for mobile, virtual and ubiquitous technologies, an Artificial intelligence (AI)-based and machine-orientation smart mobility concept was introduced. This initiative contains Connected and Autonomous Vehicles (CAVs), autonomous Personal and Unmanned Aerial Vehicles (PAVs and UAVs), and Mobility-as-a-Service (MaaS), which could work as enabling technologies for transport (Nikitas et al. 2020). Additionally, vehicle monitoring technologies play a key role, automatically collecting a range of vehicle movement data from low-cost sensors. It has the potential to well manage both passenger and goods vehicles to efficiently utilize the road system.

More importantly, the feasibility of applying city logistics under the paradigm of a Smart City needs to be tested. For instance, different road pricing schemes operating under various conditions need to be evaluated, including the impacts on freight carriers, shippers, residents, and passenger traffic (Taniguchi 2016). Likewise, one research combined electric tricycles and transshipment terminals for the last-mile delivery of parcels and small shipments. And they assessed the economic, operational, energy efficiency, environmental and social

influence of the Smart City Logistics solutions in Barcelona and Valencia. They found that the success of the Smart City Logistics project is related to the characteristics of the implemented urban area, the permitted number of packages, and the roles of different stakeholders involved (Navarro et al. 2016).

2.1.2.2 Sharing economy

Sharing economy in logistics can be described from two sides, collaborative consumption and collaborative business⁸. Collaborative consumption is defined as obtaining, giving, or sharing access to personal goods and services, coordinated through community-based online services (Hamari et al. 2016). In this context, crowd-based city logistics was investigated, and the providing services include crowdsourced delivery, extended as cargo hitching to exploit the spare capacities of transportation. Collaborative business is about cooperation between stakeholders, horizontally or vertically, and the sharing objects include data, information, knowledge, services, and assets. Operations revolutions in private sectors have impacts on public sectors, which calls for vertical collaborations. For example, an Urban Consolidation Centre (UCC) was implemented in São Paulo and demonstrated a positive impact on supply chain players (shippers, receivers, carriers) and the local population but a negative impact on the local government (Isa et al. 2021). To this end, alliances are built, and projects are launched to augment the collaboration between cities and industry to achieve lively and sustainable cities⁹. As for vertical collaboration, data sharing within public-private partnerships of city logistics has been studied as early as 2006 (Taniguchi et al. 2006). Specifically, six types of Horizontal Collaborative Transport solutions were identified to enable wider-broad collaboration, namely Single carrier collaboration, Carrier alliance and coalition, Transport marketplace, Flow-controlling entities collaboration, Logistics pooling, and Physical Internet (PI) (S. Pan et al. 2019). PI as an innovative and promising paradigm will be further discussed in the context of Digital Twins (DTs) in the next sub-section.

⁸ http://www.dpdhl.com/en/media_relations/press_releases/2014/dhl_logistics_trend_radar_2014.html

⁹ <https://www.etp-logistics.eu/strong-collaboration-between-cities-and-industry-will-pave-the-way-to-lively-and-sustainable-cities/>

2.1.2.3 Knowledge applications

The importance of knowledge description and management has been emphasized recently in the field of operations management, based on the rapid development of data techniques and information systems but bridging some gaps in data and information processing. Specifically, advanced technologies, such as ICT and IoT, can well support logistics operations by data collection, but the captured data is of a considerable amount and uneven quality, which poses a high requirement to the computation capabilities and expenses. In addition, the value of raw data needed to be extracted into information or knowledge to provide insights and influence decision-making and behavior-changing following the Knowledge Pyramid proposed by Frické (2009). With this trend, Knowledge Graph (KG) was a knowledge base to store the semantics of the entities and their relationships as knowledge representations. Ontology is the schema of KG, composed of a group of formal vocabularies that clearly define the entity categories and their relationship types. Since it is shareable and reusable, it was used to describe the knowledge in specific domains to enable knowledge propagation and build the consensus and foundation for cooperation, mitigating heterogeneity and enhancing the interoperability of complex systems. For example, Anand, et al. (2012) structuralize the knowledge in the city logistics domain to further guide the knowledge application among the stakeholders in joint value creation.

Reasoning can be done in KG to reveal the hidden facts and infer new facts, and specific operations conclude KG completion, relation extraction, entity classification, and so forth. For example, Kosasih et al. (2022) applied KG to Supply Chain Risk Management to infer the hidden links across various types of supply chain players, making the KG more complete to facilitate the complex risk queries. Knowledge application shows advantages over data processing and uncertainty handling. Wang et al. (2021) proposed a hybrid data-driven and knowledge-driven method to solve the Inventory Routing Problem. It shows the ontology-based approach has tackled the data quality problem with precise semantics, and knowledge reasoning can handle the uncertainties and unquantifiable factors well. The reasoning of KG can derive new knowledge to support decision-making and resource allocation. Zhao et al.

(2022) created a Dynamic Spatial-Temporal Knowledge Graph to allocate resources in production logistics by extracting knowledge of resources from the IoT data, reasoning the geological information in a directed and weighted graph, and using a graph algorithm to perform the optimal allocation of resources.

2.1.3 State-of-the-art solutions

Regarding the recent solutions, LSPs and city administrations have shown their efforts. LSPs and cities widely use Operations Research (OR) to support their decision-making and policy-making. From a more broad perspective, urban freight modeling was proposed to consider all the stakeholders and elements that influence city logistics operations and model stakeholders' reactions to dynamics and their interactive behaviors to build a comprehensive view and evaluate the overall performance for logistics demands. With the trend of Smart City and the development of its enabling technologies, like Information Communication Technology (ICT) and the Internet of Things (IoT), digital solutions rapidly emerge and show great potential as a game-changer in urban freight transportation.

2.1.3.1 Operations Research

Operations Research (OR) aims to apply advanced analytical methods to manage complex systems to improve problem-solving and decision-making capability. It can solve complex problems with high dynamics and uncertainties and try to find better results via various techniques, like simulation, optimization, analytics, etc. As a result, it can assist city administrations in policy-making and evaluating effects to prioritize adopting and implementing the policies. It can also aid LSPs in making better operational decisions to improve efficiencies and reduce social and environmental impacts.

City administrations pose policy measures to limit the negative impact of urban freight transport on the environment and citizens. OR accounting for the participation of multiple stakeholders and their preferences can be used to evaluate the impacts of policies. The

quantitative results can provide insights for cities to effectively design freight policies and promote the acceptability of transport operators, which will further stimulate their engagement and behavior changes. The policy measures contain four aspects, energy, regulation, land use, and infrastructure. Specifically, energy and rules are about restrictions of eco-driving, time or region access, delivery space using time, and requirement to load factor. From this aspect, potential reactions of heterogeneous LSPs and their interaction effects need to be generated by OR to support policy development. Land use and infrastructure concern the planning and investment of transport infrastructure and logistics facilities, like Urban Consolidation Centers (UCC), off-street loading bays, and delivery areas, where OR can contribute to the site selection and operational optimization.

With the aid of the decision-making of LSPs, this research is conducted under specific logistics scenarios, which keep in line with the trends and new opportunities in city logistics and try to provide insights into the concrete benefits each party can gain. Some examples of the scenarios are logistics-related resources management, such as the efficient utilization of locker boxes, pick-up points, and loading/unloading spaces. It can also include facility prebooking, (partial) recharge of Electric Vehicles, and newly operated and organized ways, like crowd-shipping and transshipment. The optimized objects are various, including routes, i.e., Vehicle Routing Problem (VRP), fleet composition (size, mix), and facilities locations (depot, parkings). The objective is to make positive environmental, economic, and social changes, namely cost savings, customer service improvement, and emission reduction. The constraints considered in the operations are the time window of delivery, the capacity of the vehicles, infrastructure and handling equipment, simultaneous pickup and delivery tasks, zone restriction (low/zero emission zone, traffic/congestion limited zone), access restriction, and exclusive lanes.

Operations Research (OR) is a powerful technique to support operational decision-making and freight policy-making. A lot of factors and constraints in actual practices have been involved. However, it performs and optimizes from a partial view, i.e., from the sight of particular stakeholders. It means that it can work better by fully disclosing the highly dynamic delivery environment and understanding the connection between the resources and cooperation among the stakeholders. In this case, OR can perform simulation or optimization

in this real operational environment, knowing the LSPs' operating performance, real-time traffic condition, time-changing infrastructure availability, and accessibility, to make a difference to stakeholders of City Logistics corresponding to the overall performance.

2.1.3.2 Urban freight transport modeling

City logistics aims at the efficient urban goods movement and modeling the processes, dynamics, and effects related to this goal is very necessary and supportive. Because of the city logistics system's complexity, many components need to be considered, namely the stakeholders involved, the modeling objective, the descriptor of the modeling purpose, and the perceptiveness to achieve the objectives. Following the research of Anand et al. (2012), the main stakeholders are the carrier and administrator, the crucial objective is efficiency, the common descriptor concerned are cost and traffic flow, and the most regularly taken perspective are behaviors, policies, and multiple actors. In response to these trends, multi-stakeholder modeling and network models are two main streams.

Agent-based Modeling (ABM) was recently adopted to describe stakeholders' heterogeneous behaviors and preferences. Here, an agent is defined as an entity played in an environment that can sense different parameters and use them for goal-oriented decision-making and reaction (Dorri, Kanhere, and Jurdak 2018). To well identify the decision-related parameters of different stakeholders, a framework has been proposed to support the ABM in the city logistics domain concerning the interests of stakeholders, including price and quality care by shippers, carriers, and receivers, and social influence concerned by public administration and citizens (Anand, Duin, and Tavasszy 2016). Especially, ontology plays a key in this study, which provides formal, shared, and machine-understandable vocabularies to manage the domain knowledge and reduce the inconsistency of model development. One of the applications of ABM is to simulate the various effects of the stakeholders' interaction to evaluate city logistics measures, such as Joint Delivery System (JDS) (Wangapisit et al. 2014), Urban Distribution Centre (UDC) (Ornkamon and Taniguchi 2018). Multi-Agent System (MAS), also named self-organized system, is not as ABM emphasizes the simulation of the agents based on operations cases and observing the insights. It aims to design

intelligent agents equipped with decision-making capability for task-solving, proper reactions, coordination, and interaction with neighboring agents. From this perspective, van Duin et al. (2020) studied the self-organizing of vehicle, parcel, and supporting platforms to improve real-time intermodal last-mile parcel delivery, which shows the advantages in delivery efficiency, robustness, and flexibility. The experiment results highlighted lower vehicle shifting, decreased total vehicle distance traveled, reduced operational costs, and reduced carbon emissions.

Network models mainly contain multi-tier networks, which aim to build a consolidation-based transport system with efficient operations and resource utilization while providing adequate services and meeting regulations. Inside, the two-tier network is the most researched. Within the first tier, goods are sorted and consolidated in the City Distribution Center on the outskirts and transferred to smaller facilities for consolidation and cross-docking. Then in the second tier, the goods are delivered to the final destinations by a different fleet of vehicles. In this type of network, due to the limited handling space and transferring time of the facilities, lots of research focus on the organization of vehicle fleet and commodity flows and routing problems, such as the works are done by Mirhedayatian et al. (2019) and Dellaert et al. (2019). Interconnected City Logistics (ICL), a.k.a. hyperconnected city logistics, is an advancement of the multi-echelon network. It aims at an open and shared system composed of multiple heterogeneous stakeholders, and the available urban logistics facilities and spaces are organized and accessed in an interconnected manner. Orenstein and Raviv (2021) studied the parcel delivery problem via ICL. It performs better than a tree-like service network while using the same amount of transportation resources but providing a better quality of services.

2.1.3.3 Digital solutions

Digital solutions have been embraced and widely applied these years to face the challenges of highly dynamic operations and heterogeneous stakeholders. Such as traffic monitoring to provide information about traffic dynamics and infrastructure accessibility and fleet monitoring to enhance the visibility of LSPs' assets and optimize the operations based on the dynamic states of vehicles. Each party, such as the previous city administrations and LSPs,

tries to provide information about the part of the delivery environment (traffic) or improve performance based on the accessible information (fleet and traffic). But unfortunately, their understanding or awareness of the urban freight transport context is still fragmented and incomplete. The reason is that the heterogeneity of stakeholders causes their data to be stacked in their silos. Thus, data integration is necessary to counter these siloed data pieces to produce an overview of the source of data generation and the context in which it operates to depict the comprehensive and time-changing urban delivery environment. As an example of the efforts for data integration, Open Data has been more and more adopted by administrations to make the data can be fully accessed and exploited by the public, which aims at liberating the value of data by their integration to innovate services and propagate knowledge. The increasing deployment of Open Data city-wide or nationwide shows its importance and growing attention, such as Paris Open Data ¹⁰ and open mobility data of Germany (Mobilithek ¹¹). These data sources vary in many categories, including transport and delivery spaces (commercial vehicle parkings). In transport, the data includes traffic reports, speed data, and travel time (Germany ¹²), the number of lanes and road width, etc. of the road transport network (France ¹³), traffic flow data of roads and rails (European Union). Besides, there are data sources about national parking locations, where the delivery spaces have been delivered (France ¹⁴), and parking management systems to announce the parking's occupancy and accessibility (Munich, Germany ¹⁵). However, there are some issues in data integration and exchange processes. Specifically, data originates from multiple sources (departments, institutions, agencies, etc.) and channels (Web, social networks, and crowdsourcing) and in different data formats (G. H. Kim, Trimi, and Chung 2014). Works have been done in academia and industries to face these challenges. For example, Ehmke et al. (2009) aggregate traffic data by cluster analysis and evaluate the quality by explorative data analysis to support routing planning in city logistics. Pirra and Diana (2019) create a specific indicator to integrate data to deliver insights about time lost in congestion. Pal and Yasar (2020)

¹⁰ <https://opendata.paris.fr/pages/home/>

¹¹ <https://mobilithek.info/about>

¹² <https://www.mcloud.de/web/guest/suche/-esults/filter/latest/categories:roads@@periodicity:FIVEMINUTLY@@periodicity:BIMINUTLY@@periodicity:MINUTLY/0>

¹³ <https://transport.data.gouv.fr/datasets/reseau-de-transport-routier-national-metropolitain/>

¹⁴ <https://transport.data.gouv.fr/datasets/base-nationale-des-lieux-de-stationnement/>

¹⁵ <https://www.mcloud.de/web/guest/suche/-/results/suche/relevance/parking/0/detail/27388340-AD5B-4AD3-A0D2-DBE83173381D>

presented a unified semantic knowledge base to foster interoperability between devices, information, and devices in the context of IoT to support supply chain management. As for industrial practices, standards need to be built to enable cooperation and competition in an interoperable business. Take an example of the ONE Order project delivered by the International Air Transport Association (IATA), which aims to integrate multiple records into a unique reference to facilitate the communication and administrative work processing between order management, revenue accounting, and delivery providers.

More broadly, information systems have been adopted to support logistics operations. For example, Transport Management System (TMS) was used to enhance transportation performance in supply chain management. It functioned with planning and decision-making in transport modes, administrative works handling, loads and routes optimization, real-time tracking during transportation, and performance evaluation through the processes. Intelligent Transportation System (ITS) aims to innovate services regarding traffic management and various transportation modes that enable users can be better informed and coordinated, leading to intelligent utilization of the transport networks. The urban area is population- and infrastructure-intensive, so the interest in urban ITS was growing and has been paid more attention to. For example, Lin et al. (2020) quantify the congestion possibility under the background of Smart City, by estimating traffic congestion via its spatial-temporal features, then routing a path with the awareness of congestion to schedule the urban traffic. Besides, ITS is more advanced with the help of the Internet of Vehicles (IoV), thanks to the prosperity of IoT applications and the fifth generation (5G) communication technology. IoV integrates all the information from the communication of Vehicle-to-Everything (V2X), where “X” refers to pedestrians, vehicles, infrastructure, networks, and devices. This information will be processed to guide and supervise driving and contribute to road safety, energy savings, and traffic efficiency.

2.2 Current applications of Digital Twin in logistics

Digital Twin was a concept that came from the practice when NASA created a duplicated

physical system at ground level to twinning the systems in space in the 1960s. Until 2010, NASA officially proposed Digital Twin as a multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its flying twin (Shafto et al. 2010). In order to advance the use of the concept in other industries, Digital Twin is more generally defined as a virtual representation of real-world entities and processes synchronized at a specified frequency and fidelity, as reported by Digital Twin Consortium in 2021¹⁶.

DT research has extended its applications from the aerospace industry to other fields, including the emerging field of logistics and supply chain management (LSCM). There is rising interest in this topic. Therefore, we investigate the state of the art of DT applications in LSCM by studying its application areas, services provided, and technological maturity to gain a comprehensive and holistic vision of how DT could enhance end-to-end global logistics. For this reason, a systematic literature review (SLR) methodology was applied to perform an in-depth analysis of a dataset of 87 selected papers.

2.2.1 Areas of application

Four areas of application were identified from the selected papers: First Mile Transportation, City Logistics, Intralogistics, and Supply Network.

Regarding transport, global or local logistics and supply chains can be segmented into *First Mile Transportation (FMT)* and *City Logistics (city logistics)*. Here we define FMT in a broad sense, which means the transportation of goods on the first leg of the supply chain from the origin of the products (e.g., factory) to the final stop (e.g., transit warehouses or distribution centers) before delivery to the final destination. In this vein, FMT is directly connected to city logistics, also known as last-mile delivery or urban freight distribution. It aims at dealing with the multi-objective optimization of freight distribution in urban areas considering service level, environmental impact, traffic congestion, transportation safety, and energy savings (Taniguchi et al. 2001).

¹⁶ <https://www.digitaltwinconsortium.org/initiatives/the-definition-of-a-digital-twin.htm>

Intralogistics (IL) refers to the storage (including warehousing and inventorying) and movements of flows inside facilities such as factories, warehouses, transit hubs, construction sites, and ports. More generally, it represents a form of optimization, automation, integration, and management of the flow of materials and information circulating within a business unit.

Slightly different from the definitions in the literature, *Supply Network (SN)* in this work relates more to the coordination of entities (DTs) within logistics networks. It is a collection of interconnected agents (suppliers, logistics service providers, customers, etc.) that interact via communications and flow exchanges to fulfill their individual objectives or common goals (Kim et al. 2015). SN coordination is crucial when multiple logistics operations must be coordinated and integrated through structuralizing and control, including transport and storage across networks.

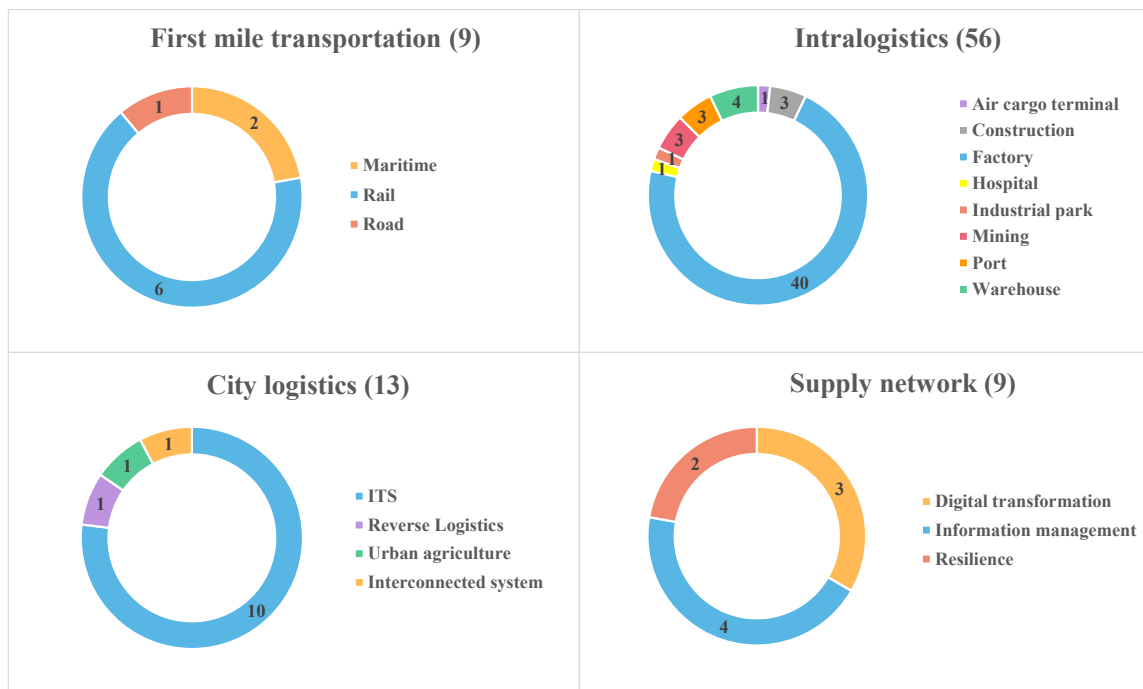


Figure 3. Paper distribution in application areas in logistics.

Figure 3 clearly shows intralogistics is the leading application area, with 56 papers out of 87. The papers on smart factories are the most numerous because manufacturing and production was the first application of DT in industry, along with the Industry 4.0 paradigm

(Qi and Tao 2018). The research mainly focuses on smart shop floors, assembly line optimization, allocation, and optimization of trolleys or Automated Guided Vehicles (AGV) for materials handling and transportation. Other noticeable research areas are warehousing, construction, ports, and mining sites.

City Logistics is the second area in which Intelligent Transportation Systems (ITS) is the dominant research focus, and DT can provide real-time traffic monitoring and analysis, traffic control and velocity prediction, route planning, accident reporting and response, and so on (Saroj et al. 2021; Hu et al. 2022; Lv et al. 2021).

In FMT, the literature has paid more attention to rail transportation than maritime and road. It shows that railway safety depends heavily on railway turnout, and DT can be used to support railway turnout system management (Kaewunruen and Lian 2019; Kampczyk and Dybeł 2021; Jeschke and Grassmann 2021). Except for the operational management of assets, maintenance can be scheduled based on vibration detection and predictive simulation (Sahal et al. 2021; Bustos et al. 2021).

Regarding supply networks, there are no predominant sub-areas according to the 9 papers selected. However, Information management and Digital transformation are both relevant to the digitalization of supply chains and logistics, which is a research trend needing more research and development.

2.2.2 Service types

Many studies consider DT technology as an enabler and driver of service innovation. For example, Tao et al. (2018) suggested nine types of product-centric services such as failure analysis and prediction, maintenance strategy, virtual maintenance, and virtual operations. These services are used for monitoring product or machine degradation and abnormal events or predicting disruptions and dynamics. Padovano et al. (2018) argued that a service-oriented DT could offer seven services to physical assets in a smart factory, and three more to workers to enhance their working experience. However, logistics and supply chain systems differ from factories because they are much more complex and interrelated, so service design should

consider more functional characteristics and requirements. Therefore, based on the previous studies, we suggest eight DT-enabled services in LSCM, namely *Real-time monitoring*, *Process analysis and prediction*, *Automation and remote control*, *Real-time decision making*, *Disruption analysis and prediction*, *Maintenance scheduling*, *System management*, *System integration and sharing*.

Table 1 gives a short description and the papers for each type.

Table 1. Description of eight service types.

Service Type	Description
(1) Real-time monitoring	Monitor the dynamic states of the physical objects and synchronize them with their corresponding DTs.
(2) Process analysis and prediction	Analyze the synchronized dynamic states of the DT to optimize and report their operational status, forecasting the subsequent processes.
(3) Automation and remote control	Produce and deliver goods or services with minimal human intervention, or operate machines from a distance instead of on-site operations.
(4) Real-time decision making	Predict, detect, and respond to real-world events based on the dynamic states of the objects and context information.
(5) Disruption prediction and analysis	Predict unplanned and unanticipated events, and analyze the effects that disrupt the normal flow of goods and materials within a supply chain.
(6) Maintenance scheduling	Track maintenance history, monitor equipment status, and schedule predictive maintenance.
(7) System management	Manage physical assets, infrastructures, workers, information, and knowledge for efficient and effective operations in an individual, enterprise-wide environment.
(8) System integration and sharing	Integrate information, knowledge, assets, and resource capacities across systems (or enterprises) for sharing, which relies on interoperability across systems.

Table 1 shows service type (4) concerning predictive analysis and decision-making has drawn the most attention and produced 18 papers. It is followed by type (7), providing 17 papers, which focus on the management of operations, assets, information, knowledge, etc., in closed systems (e.g., factory, warehouse, company). Type (8) is based on (7) and is aimed at managing the integration and sharing of information or objects across systems. An increasing number of papers are dedicated to this service type in open and collaborative logistics networks, such as resource sharing across supply chains and information sharing across stakeholders. Service types (2) and (3) have also attracted adequate attention. Both aim to enhance efficiency and effectiveness in performing operations, (2) relying on visibility and controllability of objects and operations, and (3) relying on productivity and operator safety, for example, via automatic machines and robotics. Service type (5) focusing on disruption and risk management to improve SC resilience has become a timely topic in the field, especially since the COVID-19 outbreak. The remaining two types of service, (1) monitoring and (6) maintenance, have been relatively less studied. The reasons are discussed further in Section 4.2.

2.2.3 Maturity

NASA first proposed TRL to evaluate technological readiness and risks before being used in space, with nine levels to describe the capabilities and maturity in detail. Its usage has been gradually extended to other industries. Research on DT technology in logistics is still in its infancy so the nine-level assessment might be too refined for the current research landscape. Consequently, we apply a three-stage TRL assessment of DT in the logistics industry. More specifically, the low stage (research stage) covering TRL 1-3 indicates the basic principles and experimental proof of concept. Medium stage (development stage) covering TRL 4-6 means the technology has been validated or demonstrated in the lab or relevant environment. The high stage (deployment stage) covering TRL 7-9 refers to those demonstrated or proven in an operational environment and ready for industrial deployment (Wang and Wang 2021).

Technology Readiness Level

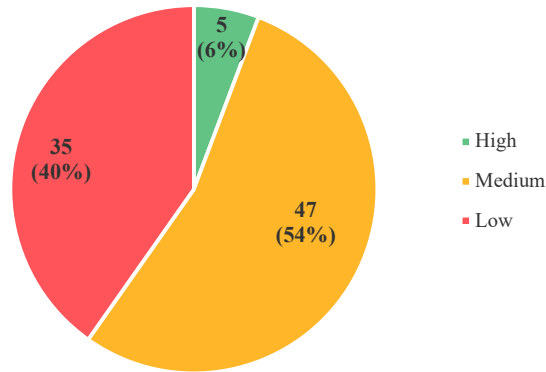


Figure 4. Distribution of the papers over the three TRL stages.

Figure 4 shows the number of papers in the dataset at each stage. The medium TRL stage takes the lead in terms of paper numbers, meaning that most DT-related studies have contributed to developing and demonstrating prototypes in a lab environment. Then, 35% of the papers belong to the low TRL research stage. Most of them focus on discussing the feasibility of DT and providing some suggestions for implementation in various areas. Surprisingly, there is very little research with high TRL (only 6% of papers). This implies that real-life DT applications are still rare. One reason is that prototypes need to be tested in a complex operational environment before real-life application, for which requirements are stricter regarding viability, therefore making the research very time-consuming. With Vehicle-to-Everything (V2X) communication, for example (Szalay et al. 2020), vehicles need to be tested in an operational environment with traffic, pedestrians, parking spaces, etc., which is a highly complex and time-consuming step.

2.2.4 Cross-analysis for insights discussion

The first results have led to a cross-axis analysis to gain deeper insights to advance DT research in LSCM. Three analytical perspectives are discussed here. The first is the cross-analysis of application areas and TRL aimed at analyzing DT maturity in various areas and exploring the strengths of DT technology that can be used to tackle issues generated from area-specific research problems. The second perspective is based on application areas and

service types, which identifies the DT function in different areas and locates service types as yet not covered to discuss the need and feasibility of developing them. The third is the cross-analysis of TRL and service types to point out the value, potential, and barriers to the development of each service. The distribution of the papers according to the cross-axis analysis is displayed in Figure 5.

Service types TRL		Real-time monitoring			Process analysis and prediction			Automation and remote control			Real-time decision making			Disruption analysis and prediction			Maintenance scheduling			System management			System integration and sharing			Total
		L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H				
First mile delivery	Maritime				1				1																	9
	Rail		1														1	1		1	2					
	Road																			1						
Supply network	Digital transformation																			1			1	1		9
	Information management									1										1			1	1		
	Resilience												1	1												
Intralogistics	Air cargo terminal												1													56
	Construction												1	1	1											
	Factory	1			4	4		1	5	1	3	6			2	1			3	5			3	1		
	Hospital							1																		
	Industrial park										1															
	Mining							2						1												
	Port									1					1			1								
	Warehouse						1			1											1	1				
City logistics	Hyperconnected system										1											1				13
	ITS		2			2					2	2	1	1												
	Reverse Logistics					1																				
	Urban agriculture					1																				
Total		4			14			13			19			9			4			16			8			87

Figure 5. Distribution of the papers according to application areas and sub-areas, service types, and TRL.

2.2.4.1 Application areas and TRL

Figure 6 presents the TRL in each area and sub-area of the application. Regarding papers, intralogistics comprises the most, in which ‘Factory’ (a.k.a. smart manufacturing) is the leading sub-area. Almost equal attention has been paid to the other areas. The main reason is that, in the context of Industry 4.0, DT was originally and primarily studied in closed-loop manufacturing systems, and its application was extended to other intralogistics sub-areas such as warehousing and terminals. However, researchers are seeking other application areas, particularly transportation (e.g., ITS and rail).

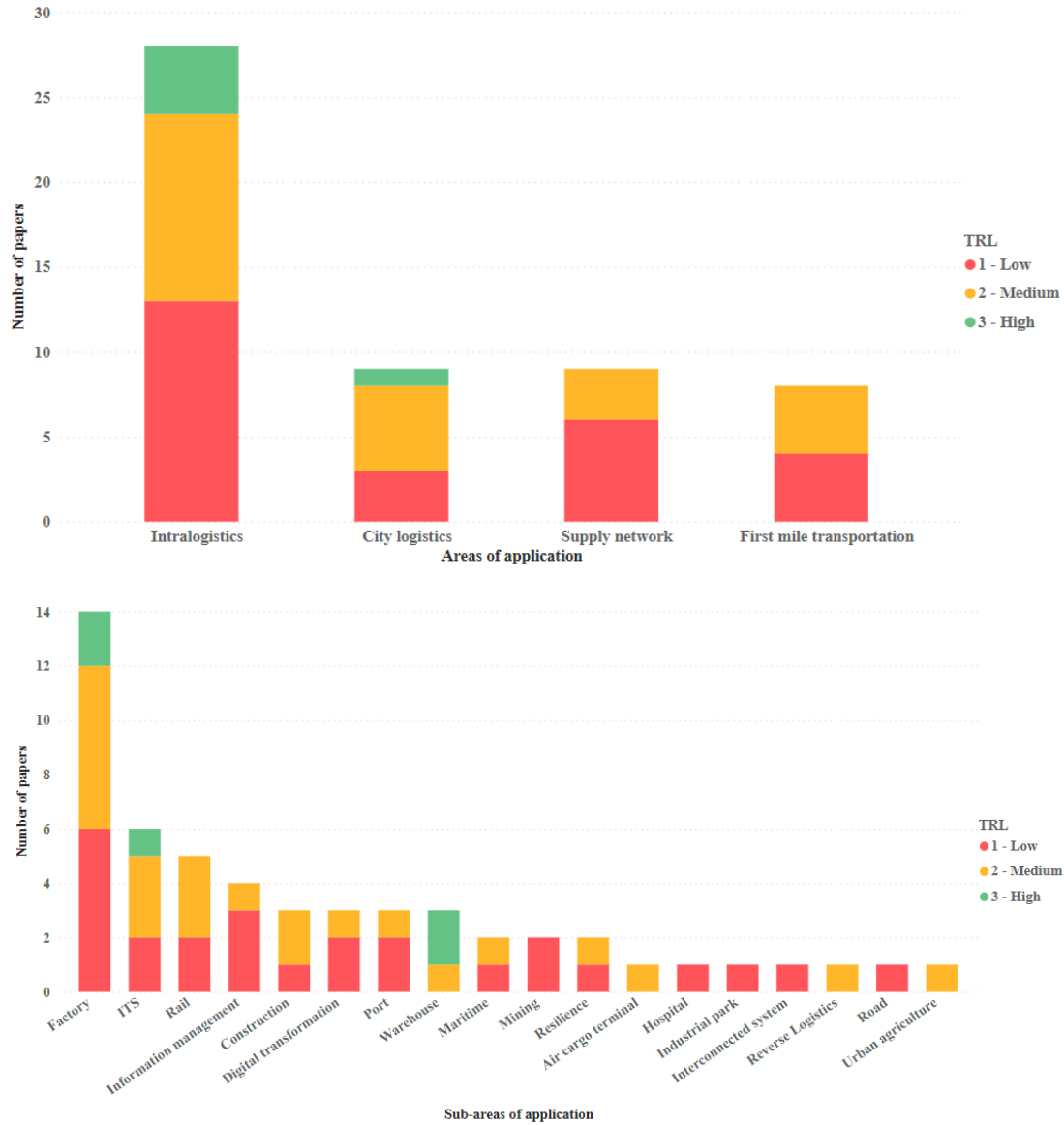


Figure 6. Distribution of papers according to the TRL and logistics areas or sub-areas of application.

Regarding technological maturity, according to the distribution of the papers in the different application areas, intralogistics has the highest DT maturity. City logistics is slightly higher than supply network and FMT, and the latter seem to be underdeveloped. Specifically, intralogistics and city logistics involve all three TRL stages, and the medium stage comprises most papers. Factory, warehouse, and ITS are the most noticeable sub-areas in these areas. Another noteworthy finding is that construction logistics is becoming an increasingly important sub-area of the application of DT. It has been intensively involved in the lifecycle

phase of built assets, where DT is advantageous for synchronizing the bi-directional data flow of building components and systems (Boje et al. 2020).

Regarding supply network and FMT, the absence of high TRL-stage research might be because both concern highly complex and open systems that are often cross-company or even cross-border; this is still a challenge for current DT technology. For example, DT is applied to handle the digital transformation of supply networks that involve a multitude of stakeholders in which the application depends closely on stakeholder collaboration at a strategic level (Opoku et al. 2021). Notably, the potential of DT has recently been investigated to improve supply network resilience (Ivanov et al. 2019). City logistics is relatively advanced compared to FMT as it has benefited from previous research on ITS and Smart Cities (Zhu et al. 2018). Overall, the analysis shows us that advances in DT technology require continuous research and adequate outputs to ensure subsequent advanced implementation then.

2.2.4.2 Service types and TRL

As shown in Figure 7, among the eight service types, real-time decision-making comprises the biggest portion of the research papers and appears to be the service type with the overall highest TRL. It uses real-time cyber-physical synchronization to make decisions based on simulation and optimization models that evolve depending on the constantly updated operational performance. This service requires interaction and coordination between the physical and virtual parts, i.e., twins, processes, environment, and connection, and also includes states and parameters (Jones et al. 2020).

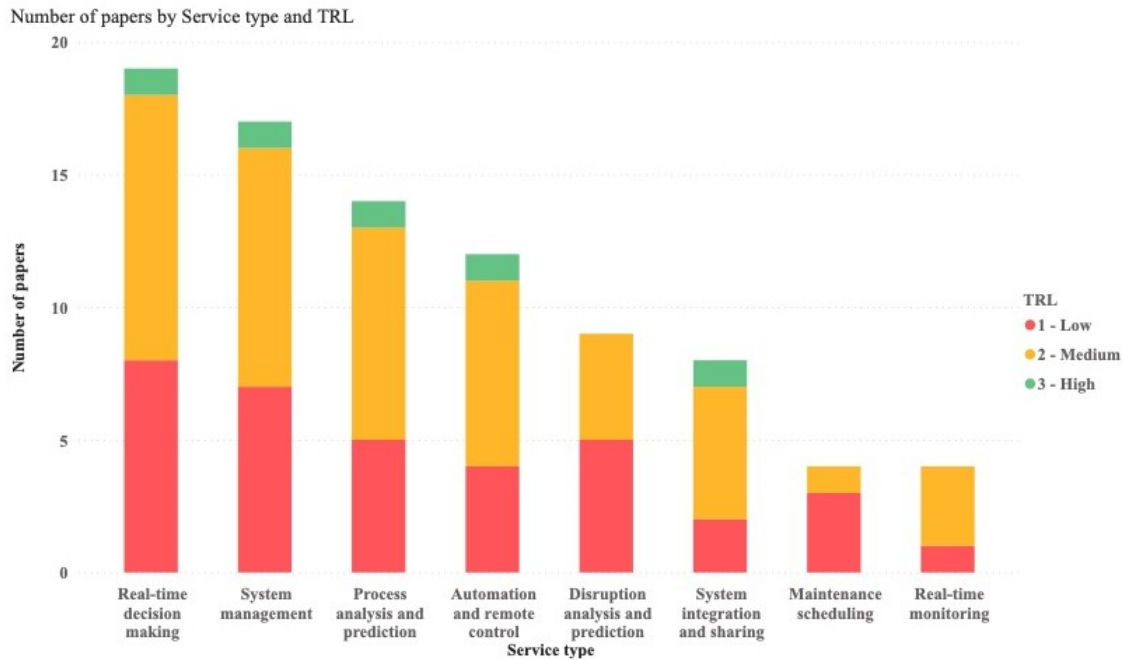


Figure 7. Distribution of papers according to the TRL and logistics service type.

Surprisingly, according to the selected papers, maintenance and monitoring are the least studied service types with low TRL. There is no doubt that DT-aided maintenance is a crucial topic for smart manufacturing. The review did not sufficiently cover the related literature as our review focused on LSCM, as defined by the list of keywords. Readers may refer to (Errandonea, Beltrán, and Arrizabalaga 2020) for a review of DT for maintenance.

From a systems perspective, System management is in second place for all the service types. It takes advantage of DT in terms of asset management, data synchronization, information exchange, and knowledge management based on data value extraction. Integration and sharing between well-managed systems have also received significant attention. Figure 7 shows that both service types have relatively higher TRL, with the presence of research in the medium and high TRL stages.

In operations management, process monitoring, optimizing, analyzing, and predicting are crucial for allocating resources and maximizing efficiency and effectiveness. Therefore, it is no surprise that a considerable number of papers deal with Process analysis and prediction and contain high TRL research. More recently, automation and remote control have been

considered imperative for advanced operations. The research interest is also rapidly growing.

Disruption analysis and prediction is another noticeable research focus, as fault analysis and risk management are key to system robustness and resilience. However, the excessive proportion of basic research, an insufficient number of medium-level studies, and the temporary absence of advanced research so far shows an immaturity of DT with regard to this service.

2.2.4.3 Application areas and service types

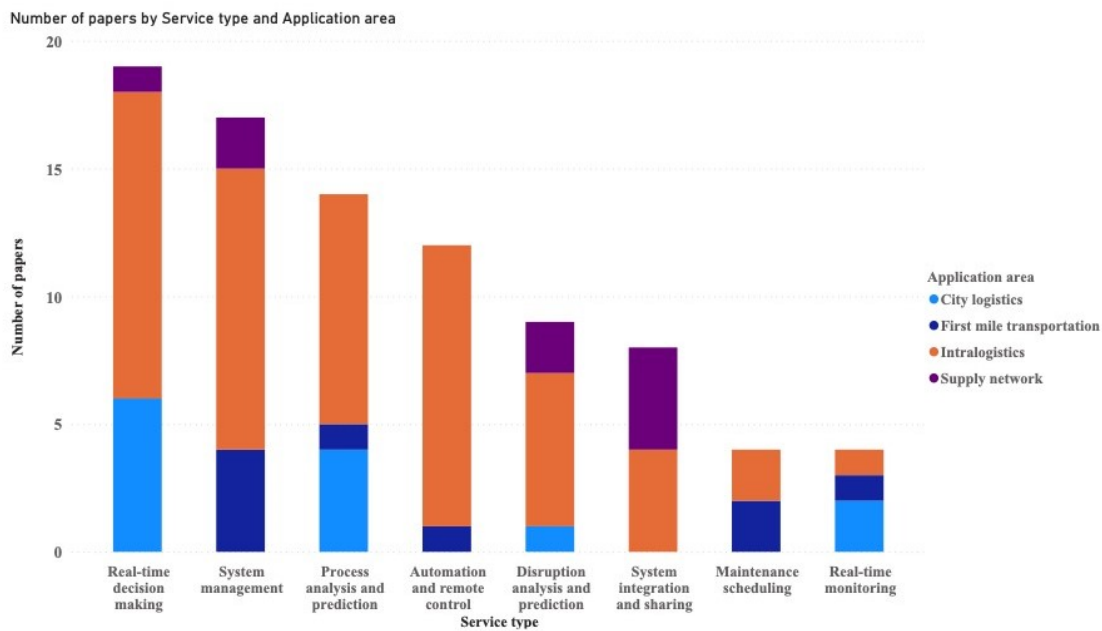


Figure 8. Distribution of service types in different application areas.

Figure 8 shows the distribution of the papers in terms of service type in each area. For intralogistics, which is the most studied area, it is no surprise that all of the eight service types have been investigated, with automation, real-time decision-making, and system management gaining the most attention. Automation in intralogistics especially is the most prominent, including AGV/AMR in warehousing (Javed et al. 2021; Stączek et al. 2021; Martínez-gutiérrez et al. 2021), autonomous transport systems in mining sites (Temkin et al. 2020; Temkin et al. 2021), and remote control of assembly lines (Leng et al. 2021). Besides, growing attention has been paid to DT-aided efficiency improvement in factories,

warehouses, or hospitals thanks to operator-robot collaboration.

As for *FMT*, five types of service have been studied (dark blue in Figure 8). The analysis shows that *monitoring*, *maintenance*, and *system management* for railway turnout assets have gained the most attention. Likewise, thanks to System management in maritime and roads, all components of transportation means can be overseen (Coraddu et al. 2021), and spatiotemporal information from transportation networks is modeled and synchronized dynamically with DT (Machl, Donaubauer, and Kolbe 2019).

Regarding City logistics, only four service types have been studied (light blue in Figure 8). Almost all research on real-time decision-making focuses on ITS. Research has focused on connection and communication between vehicles (Xu et al. 2020; Szalay et al. 2020), real-time traffic management and control, as well as recognition of user behavior and patterns and safety management (Kumar et al. 2018; Liao et al. 2021). Similarly, ITS has been the predominant sub-area for the other three types of service, i.e., Process and Disruption analysis and prediction, and Real-time monitoring, all of which concentrate on traffic management, and disruption detection and prediction to avoid congestion and accidents.

Supply network concerns highly complex networks with a large number of stakeholders compared to the other areas, which is why *System management* is applied to improve resource handling within closed systems or among stakeholders, and *System integration and sharing* for producing additional benefits through collaboration (e.g., information sharing). Moreover, supply networks rely heavily upon disruption analysis and real-time decision-making services to deal with disruption and improve resilience. Other service types are apparently underdeveloped in this area.

2.3 Potentials of Digital Twin in logistics

This state-of-the-art review has highlighted several notable gaps and opportunities for research into DT in LSCM and this research topic's vast, interdisciplinary landscape. This section discusses some promising future lines of research and applications. To this end, a schematic framework is devised to open up the perspectives of DT research in LSCM, as

shown in Figure 9. Three major research directions (with relevant emerging topics) are discussed here: DT development and evolution, services and innovation, and future logistics and supply chain practices and paradigm revolutions.

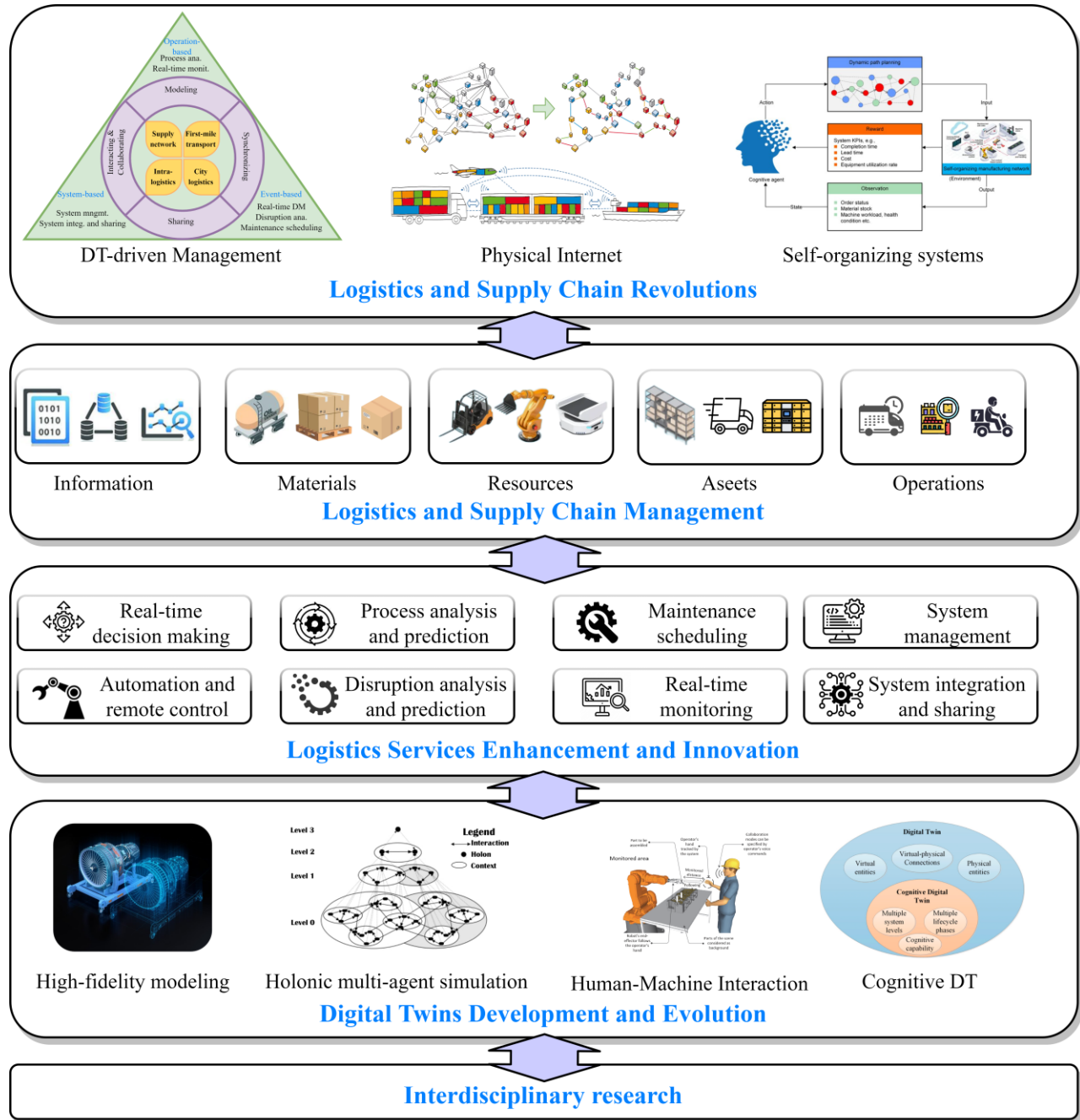


Figure 9. Perspectives of DT technology in LSCM.

2.3.1 DT development and evolution

2.3.1.1 High-fidelity modeling

DT modeling should consider the level of data granularity, consistency, and accuracy, which together define the degree of detail provided by the descriptive parameters during the transfer between physical-virtual twins and the environment. DT models with high data granularity and timely synchronization can provide more precise, real-time information about the physical entity, which is useful for the next simulation step to provide accurate information about their behavior. High-fidelity and frequently synchronized modeling is advocated in multiple product lifecycle phases but is not always affordable and feasible when considering computation time and processing power. The implementation expenses and technical difficulties may not allow a lot of parameters to be processed and transferred frequently (Jones et al. 2020). Hence, appropriate data granularity and timeliness are essential for broad connections and collaboration between DTs. Following the same rule, simulation models require DTs with different granularities and timeliness to satisfy the intended purpose of the given use case to assist system operation and service optimization.

2.3.1.2 Holonic multi-agent simulation

The DT modeling challenge is even bigger in logistics and supply chain management, which comprises highly complex systems involving numerous objects and stakeholders. Each has its own DT, the so-called System of Systems (SoS). Cyber-Physical Systems (CPS) and holonic multi-agent systems have been proposed to tackle the issue of complex systems, and when coupled with DT, result in more powerful communication and computation capabilities. The vital part of DT has been studied intensely in the field of manufacturing but merits further studies in the area of LSCM. Although CPS and DT have the similarity of intertwining physical and cyber-space, the main difference is that the former maps the physical world regarding functions to improve resource allocation and control, whereas the latter focuses more on accurately mirroring components and relationships between objects to derive better solutions and precise control (Tao et al. 2019). The complexity of logistics and

supply chains comes from the number of stakeholders with different objectives involved in the services, the loose coupling of the components, and the lack of comprehensive understanding of the whole system from modeling to operation. Such is the complexity that modeling approaches can vary for the construction of the cyber part, e.g., bottom-up or top-down. The former would be more appropriate for logistics systems with openness and plug-and-play features, whereas the latter would be powerful for intralogistics systems. The efficiency and practicability of the modeling approaches should be further investigated for each specific case.

2.3.1.3 Human-Machine Interaction

The COVID-19 outbreak has severely challenged current practices concerning managing operations and the work environment in LSCM worldwide, especially problems such as flexible operator shifts or remote work and personal protective equipment policies imposed. Moreover, the global logistics worker shortage continues to affect global supply chains. These problems will lead to higher operating costs and more difficulties in operations management. The DT automation and remote control service offer a new paradigm to deal with the problem. In the long term, DT-enhanced Human-Machine Interaction (HMI) could further revolutionize the logistics industry. HMI focuses on communication, cooperation, and interaction between humans and machines in a natural way. DT shows great potential for enhancing HMI in the product lifecycle from three aspects: a high-fidelity virtual model to support immersive human-machine interaction, using simulation data to gain knowledge about physical entities, and user-friendly interfaces (Ma et al. 2019). Collaborative robotics is one of the four DT-based HMI scenarios applied in manufacturing (Wilhelm et al. 2021), i.e., Human-Robot Collaboration (HRC), where operators and machines collaborate in close proximity to finishing tasks by sharing the same working space and resources. HRC targets higher overall productivity by maximizing the strengths of the robots (strength, endurance, repeatability, and accuracy) and humans (intuition, flexibility, problem-solving capabilities, and sensory skills) (Wang et al. 2019). For this purpose, DT-based HMI applications require the involvement of human DT in the interaction to incorporate their expertise, preferences,

and skills, as well as to analyze their posture, gestures, and locations for seamless interaction and collaboration (Sun et al. 2021). So far, most of the research mentioned above has focused on manufacturing, with only some related to logistics. However, with the development of and improvements in automation in the logistics industry, such as AGV/AMR, drones, or androids, DT-based HMI needs to be considered to best integrate humans, machines, and their DTs.

2.3.2 Service innovation and value co-creation towards Industry 5.0

DT is a disruptive technology enabling service innovation and the creation of value in industry systems. It is foreseeable that DT will contribute even more to the Industry 5.0 paradigm. The latter helps advance research and innovation from data-driven to society- and human-centric, sustainable, and resilient industry recently introduced by the European Commission (2020). DT accompanied by other technologies promises to provide a human-friendly working and training environment to exploit talents and wield skills. It is bound to make better use of the value of the human in the loop and to foster innovation and the co-creation of value by service providers or designers, end-users, and society. More human-centric system designs and applications need to be studied in this direction. For example, DT-based smart city logistics will be important to achieving urban sustainability, especially in densely populated megacities. DT-based (clean) resource and infrastructure sharing in last-mile delivery is being investigated as an efficient solution toward people-friendly and net-zero emission logistics, studied in the EU project LEAD¹⁷. Regarding resilience, DT-based process monitoring and synchronization can enhance responsiveness toward maintenance, risk management, disruption detection, and fault diagnosis. Moreover, disruption analysis and real-time decision-making services support reactions to environmental interruptions and result in a more resilient system.

Within this context, DT-based service innovation and value creation can further help improve logistics and supply chain performance via better managing the essentials such as

¹⁷ www.leadproject.eu

information and material flows, resources and assets, operators, and operations. The related literature has already proven that DT technology can help improve information and material flows management to improve the efficiency of resources and assets via enhancing lifecycle management, monitoring, planning, or sharing. Under the Industry 5.0 paradigm, it is predictable that DT can be more importantly applied to operators and operations management. It can be applied to improve the safety, ergonomics, and productivity of operators co-working with machines and robots and for continual process improvement. In turn, DT will enable machines to learn from operators to improve operational efficiency. Another example of application is training via DTs, which can benefit the trainees and trainers simultaneously. Less experienced operators can receive virtual training to reduce practical mistakes and accidents in a near-realistic environment enhanced by Augmented Reality (AR), Virtual Reality (VR), or Mixed Reality (MR). DT-based simulation can also be more cost-efficient for trainers while improving the trainee experience (Ma et al. 2019). These research directions require that the human should be considered in the loop.

2.3.3 Logistics and supply chain revolutions

It is foreseeable that DT will be a key pillar of revolutions in LSCM at all levels, including operations management, organizational models, and new industrial paradigms. This section discusses some promising and ongoing examples.

2.3.3.1 *From data-driven to DT-driven*

For several years data-driven management has been a revolution in LSCM, which aims at using historical data and relevant technologies (such as data mining or machine learning) for descriptive, predictive, and prescriptive analysis to gain insights for aiding decision-making. More recently, DT-driven management has been promoted to monitor the real-time status of objects and manage their connections in the cyber and physical world. DT-driven can be seen as a side-by-side approach of a data-driven approach since DTs are created based on data and,

in turn, supply real-time operational or simulation data for analyses. Ivanov et al. (2019) were among the first to suggest the application of DT to the supply chain, and they called it Digital Supply Chain Twin. They argued that DT-driven management could be more potent in managing disruption risks in supply chains, thanks to real-time monitoring and data generation for predictive analysis and simulation. Likewise, Pan et al. (2022) considered the digital supply chain twin as an industrial cyber-physical system (ICPS). Data and DT are two interplaying components for decision-making and system intelligence, as shown in Figure 10. They suggested that the DT-driven approach should be extended to the area of intralogistics (e.g., factory, warehouse) to inter-site and city logistics. However, the operational environment is on a large scale and much more complex. The evolution above of cognitive DT could have good potential to deal with the issue, whereby logistics systems could be more intelligent via capability improvement from perception to cognition. Further research is appealing.

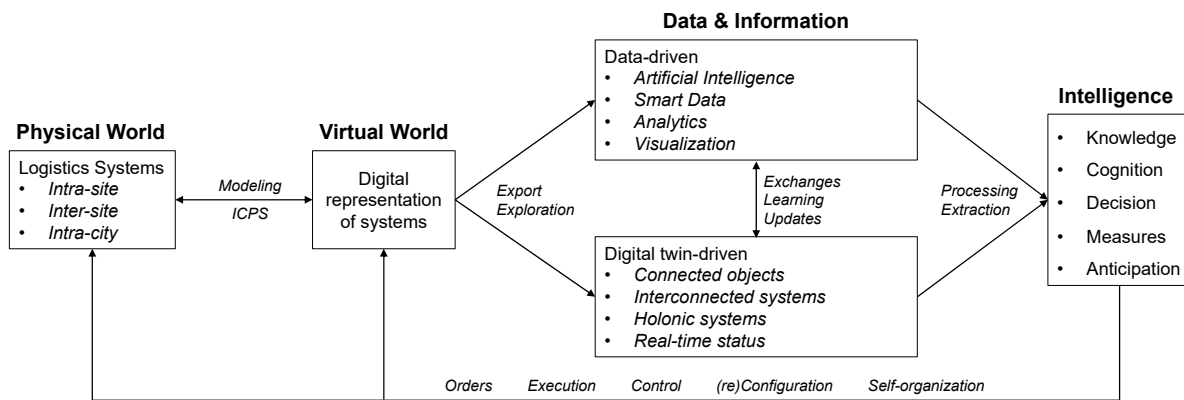


Figure 10. Role of data-driven and digital twin-driven approaches in LSCM (Pan et al. 2022).

2.3.3.2 Physical Internet

The Physical Internet (PI) is an innovative, fast-developing paradigm of global LSCM aimed at improving global logistics efficiency, sustainability, and resilience. The idea, inspired by the global digital internet for service sharing, is to interconnect currently segmented and independent logistics networks (or systems) to mutually and seamlessly share and coordinate the services, resources, and infrastructures (Ballot et al. 2014; Pan et al. 2017).

To this end, PI would consist of physical and digital parts for the movement and coordination of physical and information flows to help operations management and resource planning through sharing information in real-time regarding the states of systems and objects across logistics networks. In this vein, PI also represents a new research field, providing opportunities to make changes in LSCM through DT technology. Firstly, digital interoperability is crucial to seamless cross-company or cross-system cooperation in PI (Pan et al. 2021), and DT can be used to break the data silo effect to achieve digital interoperability. However, the effectiveness and efficiency need further investigation, especially regarding data connectivity, granularity, and accuracy in such large-scale systems. Secondly, PI suggests the interconnection of logistics networks (or systems or objects) which are usually intricately interrelated. The paradigms of CPS and DT that stress the importance of the system of systems will make important contributions to the control and coordination of objects in PI networks (Pan et al. 2022). Thirdly, DT data consistency and synchronization of different logistics systems are particularly important to PI to manage and monitor global end-to-end logistics services and disruptions. DT modeling and simulation can contribute to these aspects, especially for networking flow control and routing (Pan et al. 2022). Finally, the efficient and effective connection of the physical and digital worlds remains challenging for PI, which is particularly critical for coordinating resources and operations via the cyber world. Initial research has been conducted on the DT modeling of PI containers for monitoring across supply chains (Charpentier et al. 2021). The above research questions are only examples showing the considerable research prospects for DT in PI.

2.3.3.3 Self-organizing system

The evolution of DT towards cognitive ability could open up new opportunities to research self-organizing systems. The latter is often seen as an advanced smart system, an autonomous system that can function without significant intervention from outside the system (Bartholdi et al. 2010). Most related works have investigated the concept in the smart manufacturing area. They argued that such a system should have the ability of cognition as a prerequisite, especially at the object level for context-awareness, information analysis, decision-making,

and reasoning, to acquire the self-configuration, self-optimization, and self-healing capabilities (Lu et al. 2020). Till now, few works have tried to apply the concept to LSCM. The latter is much more complex as it may concern open and/or closed systems (e.g., global logistics, intralogistics), whereas manufacturing systems are often considered intralogistics systems. It was hypothesized that such characteristics of openness would require a system-wide effective control to avoid chaotic or other unexpected outputs of a system, even if agents are self-controlled. For example, (Pan et al. 2016) pointed out that a self-organizing logistics system (SoLS) should simultaneously have the properties of intelligence, openness, and decentralized control to make the system efficient and effective; they suggested rule-based decentralized control. In another work, van Duin et al. (2020) suggested algorithm-based control for a self-organized parcel delivery system. These works are among the others considering that agents are subjected to system-wide control rules which are predefined by a human when designing the system. However, there is a rare discussion on how cognitive agents will act in such systems. It could be hypothesized that if cognitive DT has the capability of reasoning and self-evolving, the performance of SoLS could be continuously improved as long as the cognitive DT-based agents could ameliorate the predefined rules (or algorithms). The role of cognitive DT in SoLS, and especially how they could work together to revolutionize the current LSCM, could be a significant research problem to study.

2.4 Conclusion

City logistics is operating in a population- and demand-dense area and the operational conditions are becoming more challenging because of urbanization and the requests arising from the new consumption patterns or risks, such as on-demand or instant food/groceries delivery and COVID-19. Additionally, the heterogenous stakeholders have increased the complexity of city logistics operations and their optimization from a partial view exacerbates resource constraints and city-wide inefficiencies and unsustainability. However, the advancement in technologies, while supporting the emergence of Smart City, do provide opportunities to tackle these issues, as well as the new resources offered by sharing economy that could be used for logistics purposes. Besides, technologies for knowledge application augment high-quality data processing via semantics. And it enables the building of an open

and context-aware operational environment by connecting the heterogeneous and distributed data sources into the context, i.e., the dynamic states of objects and events and their relationships, to support timely operation planning.

Current studies make efforts to handle the city logistics complexity from various aspects. Operations Research extracts value from a large amount of data through a couple of analytical techniques. It can achieve efficiency improvement and cost savings regarding the optimized objectives. However, based on the historical data collected, and the constraints set from a limited view, the optimization is partial and incomplete, it calls for more high-quality data and more understanding of the goals of other stakeholders to make a trade-off for the overall objective. Urban freight transport modeling delivers more perspectives about the importance of agent (stakeholder)-based modeling and an interconnected (logistics-related resources and infrastructure) and open environment, in which the interoperability among stakeholders and heterogeneous resources is a crucial issue. Digital solutions are more focus on the data or information sharing between stakeholders to enhance collaboration, sharing via Open Data from city administrations to increase the understanding of the urban environment. Besides, the building of Information Systems (IS) is a widely adopted solution, but the interoperability between systems results in several problems, such as siloed data and independent operations management.

Digital Twins (DTs) act well in the functions of data capturing and synchronizing, analyzing, or simulation for problem-solving solutions. Specifically, it works by mirroring their physical entities regarding the permanent attributes and dynamic changes, and DTs are equipped with executable simulation models to provide solutions to master the complex operational demands. More importantly, semantic DTs can be easily integrated and networked, which will help build the operational context to increase the overall understanding and issue identification for multiple stakeholders and enable inner communication and interaction for their collaborative operations.

So in the following chapters, the application of advanced technologies will be explored to face the challenge of interoperability among stakeholders and their systems to establish an overall understanding of the city logistics operational environment and enable the

collaboration and interaction between stakeholders and the dynamic environment to support operation planning and freight policy evaluation.

CHAPTER 3 Cognitive Smart City Logistics: concept and framework

Résumé

Dans ce chapitre, nous approfondirons nos recherches sur la base d'études de pointe afin d'explorer comment la technologie des jumeaux numériques peut aider les opérations logistiques des villes. Tout d'abord, la logistique urbaine intelligente cognitive sera conceptualisée en définissant et en expliquant clairement ses composantes essentielles. Ensuite, un cadre sera proposé pour réaliser les fonctions de la CSCL et ses composants étape par étape. Enfin, les caractéristiques de la CSCL seront soulignées et mises en évidence. Ce cadre d'architecture guidera la mise en œuvre de bas en haut, ce qui sera démontré dans les deux chapitres suivants.

Abstract

In this chapter, we will further our research based on state-of-the-art studies to explore how digital twin technology can assist city logistics operations. First, Cognitive Smart City Logistics will be conceptualized by clearly defining and explanation about its crucial composing. Then a framework will be proposed to realize the functions of CSCL and its components step by step. Last, the characteristics of CSCL will be emphasized and highlighted. This architecture framework will guide the implementation from bottom to up, which will be shown in the next two chapters.

3.1 Introduction

In this thesis, we suggest CSCL as *an integrated semantic 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 such definition implies that CSCL is to connect and integrate city-wide logistics objects

for operation management thanks to various technologies. The technologies may mainly refer to Information and Communications Technology (ICT), the Internet of Things (IoT), Semantic Web, and most importantly Cognitive Digital Twins (CDTs). The logistics objects are physical entities involved in city logistics, such as vehicles, parcels, roads, parking, deliverymen, and so on.

Significantly, the “cognition” comes from the Cognitive Digital Twin (CDT), the semantics-augmented DT, benefiting from semantics and DT at the same time, the differences between DT and CDT are shown in Figure 11 (Zheng et al. 2021). CDTs will play as the atoms of the city logistics system to produce a Cognitive Smart City Logistics (CSCL) system, where semantic interoperability is provided to connect CDTs and integrate them into the context in which they are operated. The cognition capability is shown as semantic interaction (queries) with the context to achieve efficient logistics operation planning and sustainable urban resource allocation.

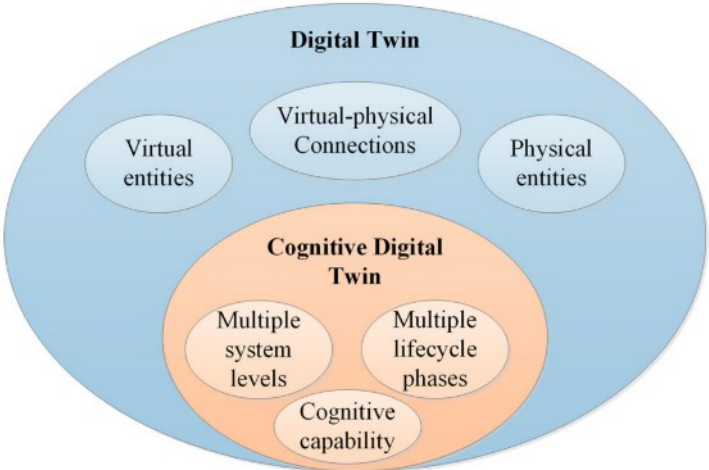


Figure 11. Relation between the digital twin and cognitive digital twin (Zheng et al. 2021).

Two research streams are crucial to the rise of CSCL: digitalization and data analytics. Regarding digitalization, CSCL requires both sides of the delivery environment (the city) and key players (shippers, LSPs, clients) to be digitized. The digitalization of the delivery environment is essentially relying on the Smart Cities context, see the framework in (Pan et al.

2021) and a recent survey on the State-of-the-art IoT/ICT technologies for Smart Cities by Garcia et al. (2018). The digitalization of logistics has been a hot research topic for years. Most works attempt to apply IoT solutions to manage logistics operations, for example, wearable devices for warehousing and distribution (Luo et al. 2021), and IoT-based crowdsourcing for on-demand food delivery (Tu et al. 2020). As a practical example, an current EU H2020 project LEAD¹⁸ aims to build and integrate the Digital Twins of city infrastructures and logistics systems for logistics efficiency improvement. As for data analysis, Taniguchi et al. Taniguchi et al. (2020) suggested analyzing the collected precise data on the movements of goods and vehicles with innovative technologies. It includes Big Data (BD) and Artificial Intelligence (AI), which results in an Intelligent Transportation System (ITS) to improve the efficiency and sustainability of urban freight systems. In addition, Yang et al. (2019) proposed an auction-based parking allocation and pricing solution, with readjustment considering the traffic dynamics and the resulting uncertainties of carriers' arrival time. And based on the analysis of the information from the heterogeneous carriers, it shows significant social benefit, i.e., 22% of the social welfare improvement.

In summary, there is rich literature concerning data collection and usage to improve decision-making and operations management in city logistics. Being a predictable future evolution, and from a comprehensive perspective of managing the city, it calls for an interconnected and cognitive logistics network, which is crucial to enable and automate the accessibility to urban resources and allocate them efficiently and effectively. This work will explore how to build such a network by connecting the objects in the Web of Things (WoT) context and utilizing semantic technologies to enhance interoperability and openness, enabling their communication and interaction in the complex system. We argue that cognition capabilities of DTs would be crucial to efficient and seamless interoperability in such smart systems.

¹⁸ <https://www.leadproject.eu/>

3.2 From semantic to cognitive Digital Twins

3.2.1 CDT concept

Cognitive DT (CDT) is a novel concept extending the conventional definition of DT by enhancing its semantic communication and interoperability capabilities with context awareness for self-adaptation and self-decision-making. It is distinguished from DT by the additional perception capabilities through standardized object representations, attention via clearly defined goals, memory through information storage, problem-solving, reasoning, and learning (Zheng et al. 2021). Several research topics relating to this concept could be investigated. First, CDTs should have the ability to autonomously connect to and communicate with other CDTs or similar smart systems, relying on standardized protocols and semantics technologies. Ontology, one of the Semantic Web solutions, offers support for the abstraction and conceptualization via formal, explicit, and shared vocabularies. For example, a freight parking service provided by semantic-enhanced DTs works to improve infrastructure connections managed by administrative and urban parking resources (Liu et al. 2021). This topic is relevant to the recent concept of the Web of Things, which puts more emphasis on the integration of operable and controllable objects across the IoT platform and applications. Second, CDT equipped with problem-solving capabilities can be achieved using Knowledge Graph (KG). KG is often used to describe and enhance ontology-provided knowledge about entities, relationships, properties, and events within a domain, infer new facts by reasoning, and supply knowledge for the evolution of CDTs. Some recent studies have started investigating the combination of DT and KG for resource allocation in manufacturing systems considering real-time spatiotemporal constraints and requirements (Zhao et al. 2022). Likewise, KG-based Digital Twins of the United Kingdom (UK) are developing to perform cross-domain simulation and scenario analysis. Specifically, it aims at the optimal use, planning, and development of infrastructure, and analyzing various scenarios to help the government achieve its development objects (Akroyd et al. 2021). This state-of-the-art research shows us the potential advantages to combine the capability of semantics and digital twins. Therefore, CDTs, semantic digital twins, will play a key role in our research to enable Cognitive Smart City Logistics.

3.2.2 Four characteristics of CDTs

CDTs are DTs augmented with semantics, so it composes the traits of DT and semantics at the same time. First, regarding the individual DTs, each of them has a physical twin, digital counterpart, and mutual interconnection, which enables their bi-directional communication. More importantly, the simulating capability was emphasized by many recent works, as studied by Boschert and Rosen (2016) and Agalianos et al. (2020). Semantics is the main advancement from DT to Cognitive Digital Twin (CDT). Semantic technologies provide individual DTs interoperability to integrate into the whole operating environment, and also empower them to aware and interact with this context. Thus, semantic interoperability and context awareness are two more advanced traits that CDTs have.

3.2.2.1 Bi-directional

The basic components of DT mainly contain three parts, *physical entity*, *digital replica*, and their mutual *connection*. While some research separate *data* feeding DT up and *services* provided by DTs as two independent components, such as mentioned in the work of Qi et al. (2021). In the physical space, the sensors and tags will capture data to describe the object states in various parameters. These data will synchronize and make changes to the digital twins in cyberspace to keep the consistency and orchestrate with the physical counterpart. DTs can perform analytics or simulation of dynamic events, and provide the potential problem-solving responses to support decision-making. This made decision will be re(act) to the physical twins via actuators, which means bi-directional communication between physical and digital twins has finally given a prescription and influenced the physical world.

3.2.2.2 Simulating capability

As stressed in the work of Zheng, Lu, and Kiritsis (2021), the key difference between CDT and DT is that CDT is performed on the basis of multiple lifecycle phases and multi-scale and

cross-systems. This more advanced and complex system aims at cross-domain simulation and decision-making. Just as Akroyd et al. (2021) studied the universal digital twin, which can connect the building data, transport flows, underground infrastructure, humidity and temperature data within the urban area via interoperability. It can not only process these multiple sourcing data but simultaneously consider the various objectives to support urban design and planning. Likewise, Rosen, Boschert, and Sohr (2018) proposed the next generation of digital twins, which emphasized the importance of the simulation capability of DT in complex and multi-scale systems. They pointed out that DT can mirror the states of their physical counterpart to well support the management, but it needs to be highlighted the other function of DT, is to drive solutions based on the monitored object state changes or dynamic events via simulation. Figure 12 has shown the relationships between DTs, multi-scale systems, and simulation models. Hollow solid line dots represent the DT corresponding executable simulation model. Digital artifacts signify the permanent attributes and dynamic properties of objects. At the same time, the objects and systems will be in different states with time changes, such as development, operations and maintenance, so that their availability and accessibility is also changing during the collaboration of other DTs.

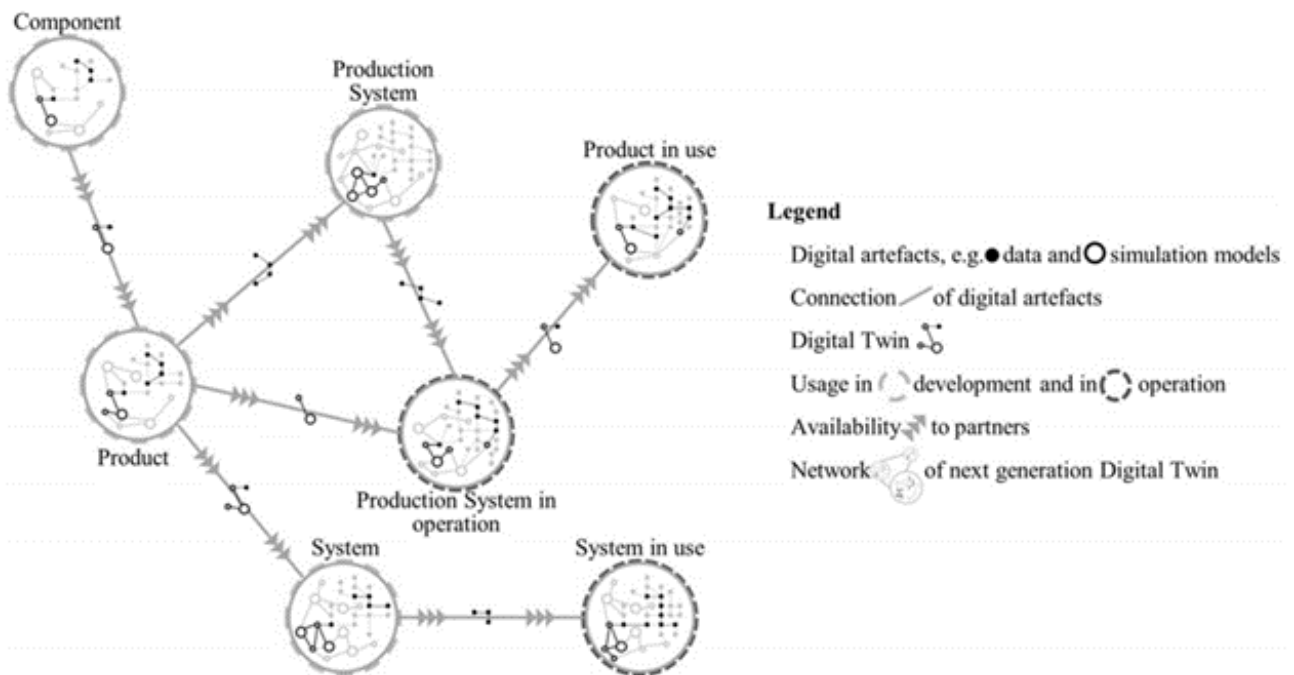


Figure 12. The relationship between DT, simulation models, and multi-scale systems (Rosen, Boschert, and Sohr 2018).

3.2.2.3 Semantic interoperability

Semantic technologies support DTs develop towards CDTs. A series of technologies shown in the semantics web stack (Figure 13) aims at making the data not only readable for machines, but make it understandable and accessible by providing unambiguous meaning. The data meaning processing is supported by a set of standard conceptual vocabularies, also named ontology, which are the conceptual abstractions of the data and exists above the specific design of databases. It provides convenience to integrate separated and distributed DTs into the networked CDTs. Also, on this solid bases, i.e., interconnection, not only data can be shared without obstacles but the mutual communication between CDTs has been enabled to support the operations management. Thus, it shows the feasibility of semantic interoperability in integrating heterogeneous stakeholders and the data pieces stacked in the silos, in order to ultimately support resource and operations management.

3.2.2.4 Context awareness

Context herein can be defined as a dynamic operational environment, which contains lots of objects in city logistics, and object states as well as their inner relationships are always changing. The importance of context to CDTs cannot be overstated, since it is indispensable for CDT to make accurate responses and reactions in the dynamically and quickly changing environment. The context-awareness can greatly promote CDT to develop cognition capability since it can support CDT make decisions in a more human-like way. In other words, it closely depends on context information, influenced by the different timing, relevant objects' states, and CDTs' own dynamic states, the responses are varied in different contexts even though towards the same task. Thus, enabling CDTs with context-awareness can help them understand the consistently changing operating environment and support them in simulating and providing problem solutions.

Hribernik et al. (2021) regard context awareness as one of the important directions of DT. They emphasize the significance of the context model to DT, which works for efficiently and effectively organizing the context information received by DTs. This information comes from the state and relationship changing of the DT-related objects. It needs to be noted that the graph-based model is recommended to reflect the operating context, which can be seen as a support for our modeling approach, Property Graph (PG). On this basis, when these context-aware capable DTs have been aggregated, they can conduct real-time dynamic decision-making based on this multi-sourcing context information, which will make a revolutionary difference in the DT capability.

Elayan, Aloqaily, and Guizani (2021) proposed to use DTs for intelligent context-aware IoT healthcare systems. DTs of patients will consistently monitor their health status, and identify the risk factors or predict the possibility of diseases based on the fluctuating parameters. In addition, patients' DTs will involve professional experts in providing prescriptions to patients. More crucially, their proposed model can integrate the historical, present, and predicted patients' data together, and compare them with current similar cases, in order to provide more effective support for experts to make decisions and give prescriptions in patient health management.

3.3 Architecture framework of CSCL

Based on the concept of CDTs, we propose an architecture framework to implement CSCL in the Smart Cities and Web of Things (WoT) paradigm (see Figure 14). The layered framework adopts a bottom-up modeling approach, whereby physical logistics systems are first translated into digital twins with details of objects and operations, then integrated into the smart delivery environment via semantic technologies. A series of semantic technologies are shown as a stack in Figure 13 (Szilagyi and Wira 2016).

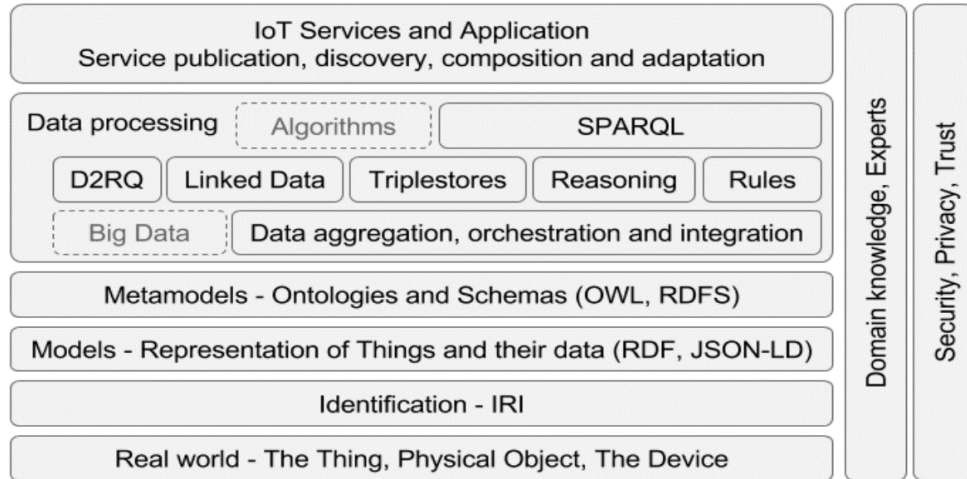


Figure 13. Semantic Web Stack for IoT (Szilagyi and Wira 2016).

The details of each layer will be presented as follows.

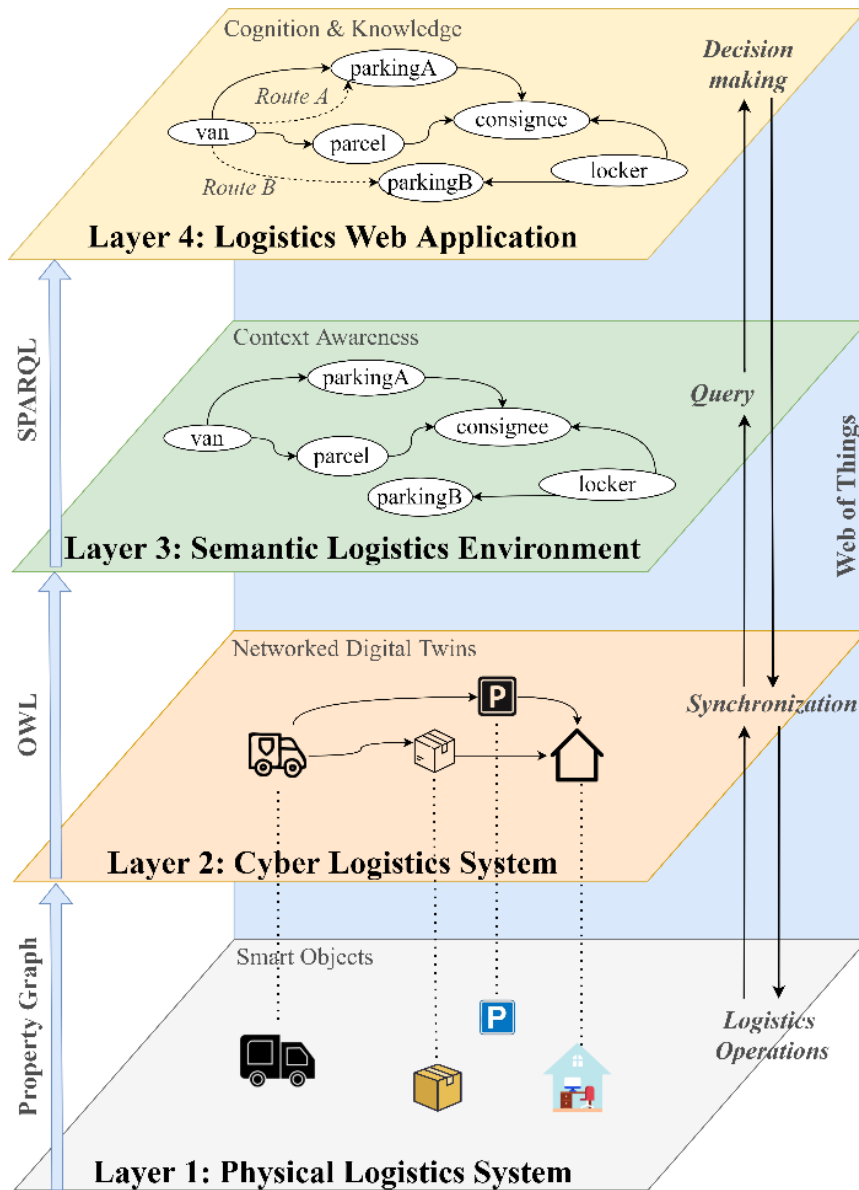


Figure 14. Architecture framework of Smart City Logistics Web.

3.3.1 Layer 1 & 2: Cyber-physical logistics system

In *Layer 1 Physical Logistics System*, we first conceptualized city logistics applied scenarios and then figured out the relevant smart objects, i.e., objects with sensors or tagged products. Moving up to *Layer 2 Cyber Logistics System*, objects and their connections are modeled with Property Graph (PG), which was proposed by Privat et al. (2019) as the best existing model to describe Cyber-Physical Systems in IoT or WoT environments. With the

modeling approach PG, the physical objects are twinned into the cyber layer as the networked Digital Twins. It needs to be noted that this model can clearly define the system but is still owned by specific stakeholders, for example, individual LSPs. Although without any openness, modeling until this stage provides an excellent foundation to share the self-own system on a joint base, i.e., Property Graph, with other systems for communication and collaboration. Besides, IoT data or open data sources are necessary to be injected into the system for real-time state monitoring and decision-making regarding dynamics.

3.3.2 Layer 3: Semantic Logistics Environment

In Layer 3, Web Ontology Language (OWL) is used to define the objects and concepts and then describe the logistics system's knowledge. Ontology is a formal, explicit specification of a shared vocabulary (Studer et al. 1998). The semantic logistics system can communicate with the context, i.e., shared systems or objects, such as infrastructures or assets, stakeholders' systems, etc. Modeling procedures and queries from the semantic environment have been illustrated in our former research (Y. Liu et al. 2021). This layer is most important under the background of Smart Cities where WoT is present. A query language like SPARQL can be used to query the ontology in Layer 3 (Xiao and Corman 2021).

3.3.3 Layer 4: Logistics Web application

Logistics applications in the environment of WoT make decisions (e.g., parcel assignment, routing) or conduct analysis after dynamic information updates, including object states synchronization and semantic communication. And then perform simulation, optimization, and prediction to provide operational solutions based on the information gained. *Layer 4* combined the dynamic status of CPS (*Layer 1 & Layer 2*) and query results from the Semantic Layer, to make decisions based on the more comprehensive information and knowledge of the whole system and the context. And then the decisions will be communicated to the corresponding avatars located in *Layer 2*. After the status synchronization of the digital twins, the physical objects will react or change their behavior in

Layer 1.

This framework shows a close loop in which the digital world controls and reacts to the real world where the timely dynamics are generated. The processes are from modeling of CPS for information management and controllability of objects, gaining an understanding of the operational environment via semantic communication, and then making decisions based on the overall comprehension. Finally, synchronized with DTs to update their states, which results in the decided solutions performed in their physical counterparts, which makes the changes to the real world.

3.4 Three salient characteristics of the architecture

3.4.1 Real-time dynamics

Objects have permanent attributes and time-changing properties. Take an example of a vehicle, the vehicle type, size, the energy type it used cannot change during the operation, but on the other side, the location, loading capacity, energy balance, and health states can be different. Therefore, in our modeling, these permanent attributes will be modeled only once and kept the same for the rest lifecycle, but the dynamic states will be updated with a specific time interval to support the real-time operation. The various time intervals depend on the cost-effectivity, and timeliness of the data needed for operational decision-making. For example, traffic congestion needs to be noticed within up to five minutes, and the parking availability and traffic lighting information need to be updated every minute (Zanella et al. 2014). The timeliness of these data will influence the stopping locations and (re)routing of the vehicle and the adjustment of the parcel delivery sequences. This timeliness will be specifically reflected in the synchronization from Layer 1 to Layer 2, where the smart objects update their states via the IoT devices.

3.4.2 City-wide Systems of systems

In the current city logistics operations, the LSPs have self-owned Information Systems to

support the monitoring, analysis, and optimization of their assets and processes. For this reason, *Layer 1 & 2* are performing very well as Cyber-Physical Logistics Systems (CPLS) in the individual and independent operation from a limited view and with as much information as the system owner can get in this position. However, LSPs and other stakeholders can possibly gain benefits from building openness and shareability to interact with the whole operational environment. For example, via the interaction, LSPs can profit from the cooperation with other partners to consolidate goods flow and improve delivery efficiency, and city administrations can obtain insights about the real operation situations for urban planning and freight policy-making, which with more expectations for the most extent collaboration from the industries and eventually make positive impacts on society and environment.

Therefore, the function of *Layer 3* works for this goal, building openness of the CPLS and providing interoperability for their further interaction. For this purpose, semantic technologies need to be implemented in the modeling of *Layer 2*, so that digital interoperability will be enabled and provided in Layer 3 for the integration (data, information) and communication (logistics demands, resource states) with other stakeholders' systems. This integration will be conducted by interconnecting stakeholders' shared objects regarding their relationships, this relationship will be described by the schema provided by an *ontology*. For example, vehicle *a* will deliver parcel *b* to destination *c* via a short stop in parking *d*. LSPs possess the vehicles and operated parcels regarding their destinations, while city administration is responsible for managing the utilization of parkings by certain rules and keeping the accessibility informed to the public. Objects (classes of objects) *a*, *b*, *c*, and *d* are owned by two stakeholders but based on the interoperability provided by semantics, they will be interconnected following the ontology schema after the two parties' sharing. Thus in this interconnected environment, the operation can gain timely support whilst city managers can be announced the operating performance for evaluation and urban planning.

This interconnected comprehensive environment is named a *System of Systems* (SoS), also named a *collaborative system*, where a *system* was defined by IEEE as a collection of components organized to accomplish a specific function or set of functions. And the composition of SoS follows two principles: operational and managerial independence of the

components (Maier 1998). For example, the Interconnected City Logistics system without a single and obvious authority is an SoS while a fleet of vehicles is not. Because the components of the ICL system, namely TMS, urban ITS, etc., operate independently even if disassembled from the overall system and managed for their own purpose rather than the whole. But the vehicle, as a component of the fleet, does not have both operational and managerial independence. From this view, Andersson and Rylander (2022) stress the generalizability and interoperability of building SoS after a three-year urban consolidation project involving various stakeholders in alleviating environmental challenges in city logistics. Thus a semantics-based approach shown in this thesis can well handle the objective of SoS's integration and interoperation.

3.4.3 Knowledge description and management for cognition

Urban freight management quite depends on awareness or knowledge about the objects, events, and rules in the operational environment, such as the real-time dynamics (traffic jams, accidents) and the regulations (LEZs, access-limited areas). And then, it is essential to transfer the awareness and knowledge into the cognition of the environment to make behavior changes in the day-to-day operation and sustainable urban management.

Following the DIKW model (Frické 2009), data collected from sensors and information from the outside environment will be used to build the context, where these data and information came from. From this aspect, it stresses the amount of high-quality data, which could be understood as gaining more useful pixels (valuable data) for the higher-resolution picture (context). As enablers, *semantic technologies* provide machine-readability and -interoperability standards for data quality management. The processed data and information can contribute to building context awareness, i.e., knowledge of the environment. For example, the raw data from the traffic light showed a signal of “red”, and the information shows the meaning is that “the traffic light has turned red”, moreover, when related to the context, it will be processed into a knowledge level, which is “the traffic light I am driving toward has turned red”. After translating the raw data to this extent, the cognition capability is called to make reactions to the environment, which in the example is “The traffic light I am

driving towards has turned red, I would better stop the car.”

Cognition indicates intelligence or wisdom being similar to or imitating humans when responding or reacting to changes in the environment. It locates at the top of the DIKW model based on data value extraction, information, and knowledge management. Cognition-related operations are decision-making, self-cognition, self-adjustment, self-(re)configuration, and so on. Currently, the most common study field of building “cognition” is Artificial Intelligence (AI), especially Machine Learning, which works to evolve cognition to higher wisdom, in order to achieve better behavior or reaction to the dynamics or disruptions from the environment. In addition, since the 1980s, AI researchers have proposed *ontology* as a modeling approach and as a component of knowledge systems that enable automated reasoning (Gruber 2009). *Semantic technologies*, composed of *ontology* as a crucial part, show a promising and potential way to build cognition capabilities in recent studies. It functions by sensing unforeseeable behaviors via context awareness, and reasoning for optimization strategies that can lead to the continuous evolution of the system (Zheng, Lu, and Kiritsis 2021). For this reason, the Cognitive Digital Twin (CDT), the semantics-augmented DT (Zheng et al. 2021), will be used in this context to benefit from semantic technologies and DT at the same time. It will play as the atom of the city logistics system to produce a Cognitive Smart City Logistics (CSCL) system. Specifically, semantic interoperability will help to integrate CDTs owned by different parties into the operating environment, a.k.a. operating context (Ganzha et al. 2017). The “cognition” specifically presents in CDTs with being aware of the context where they operate and perform semantic interaction regarding the logistics needs. The interaction results can support CDTs to make decisions and perform reactive behaviors.

In the former studies, the awareness of the operational environment has been called for participate policy innovation and making (Stathopoulos, Valeri, and Marcucci 2012; Gatta et al. 2019). It involves logistics operators in the decision-making processes by first letting them know about the freight transport issues and then presenting their preferences. The goal is to improve the freight policy design and analysis to stimulate stakeholders’ acceptability and foster their behavior changes. In fact, to achieve these goals, the context information captured from IoT devices can well build the context-awareness, which works for the objective of

“known”, and the cognition capability will target the “behavior change”, which will be empowered by semantic technologies through a series queries on the relationships of the context entities (Gu et al. 2020). For example, some delivery vans with emission monitoring sensors are driving in an occupied area, the context information includes the driving vehicles' locations and the road network congested degree, the destinations and the related-parkings, the expected delivery time, and the availability of the consignees. For *LSPs*, the cognition capability will query the relationship between the destinations and parkings, and the properties of parkings (type, availability...) and provide the deliverymen with available options regarding walking and driving preferences. For the *customer*, if the Estimated Arrival Time (ETA) exceeds their expectation, the queries will perform over the relationship between the consignees and their delivery alternatives (mailboxes, neighborhood, collect points...) and then ask for authorization and permission to confirm the alternative solution via the connection with their smartphone. Based on the information from context and cognition performed queries, i.e., vehicles and roads, the parkings and destinations, expected delivery time and the ETA, deliverymen's delivery choice, customer's delivery decision, and timely data of produced emissions to the area, the cognition capability can provide a comprehensive report about the external costs of the undergoing deliveries to the *city administration*, if the cost is excessive to a threshold value, it will query the nearby roads and vehicle speeds to find if an exclusive lane can be kept for these delivery vans, or query that if there is a subsidy can be provided under this external cost for inducing deliverymen to choose the walking-priority solution.

CHAPTER 4 Approaches and technologies for CSCL modeling

Résumé

Le chapitre examine les approches de modélisation et les technologies clés qui sont appliquées dans cette thèse pour modéliser et mettre en œuvre le CSCL. Il convient de préciser que le CSCL, en tant que nouveau paradigme pour la logistique urbaine, ne doit pas se limiter aux approches ou aux technologies examinées ici, et qu'il doit évoluer avec les nouvelles approches ou technologies issues des chercheurs et des perspectives transdisciplinaires.

Pour donner une idée plus concrète, le chapitre commence par un cas d'utilisation conçu pour évaluer l'applicabilité et la performance du cadre proposé. Ce chapitre ne décrit que de manière générale le cas et les approches de modélisation du système et des éléments. Plus de détails sur la modélisation de la prise de décision seront donnés dans le chapitre suivant concernant les études quantitatives et qualitatives.

Abstract

The chapter discusses the modelling approaches and key technologies that are applied in this thesis to model and implement CSCL. It should be specified that CSCL as a new paradigm for city logistics should not be limited to the approaches or technologies discussed here, and it should evolve along with the new approaches or technologies resulting from transdisciplinary researchers and perspectives.

To give a more concrete idea, the chapter starts with a use case that was designed for assessing the applicability and performance of the framework suggested. This chapter will only generally describe the case and the system and element modelling approaches. More details about decision-making modelling will be given in the next chapter regarding quantitative and qualitative studies.

4.1 Use case – freight parking management

4.1.1 Introduction

Parking issues have a significant influence on delivery efficiency and costs. It has been regarded as an important factor in delivery driving, and the research on freight parking can both benefit LSPs and city administrations in understanding how the driver behaves and the impact of freight traffic on the urban environment (Wise et al. 2019). However, the delivery practice in the real world is under expectation. For example, one research shows the useless cruising time downtown for parking accounts for 28% of the whole trip time (Dalla Chiara and Goodchild 2020). The vehicle is parking on the curbside (on-street parking) for around 60% of the total journey time. The deliverymen need to walk on average 8 kilometres daily without counting the vertical distance (staircases in buildings), which takes a portion of 30% of the total journey distance. And there is a huge difference in efficiency between experience workers the naive ones, which is 50% in distance traveled specifically (IET 2019). Therefore, it shows a great need to study for the improvement of the freight parking regarding the working conditions of the deliverymen, and use the technologies to improve the efficiency by increasing deliverymen's understanding of routes and locations in driving and walking.

4.1.2 Use case design

Kevin is a deliveryman in Paris. His day starts with all parcels and drivers at the depot, with parcels transported overnight to the depot and organized based on their round and geographical districts. In the morning, Kevin lines up his parcels and scans each parcel with his terminal as he loads it onto his van. Kevin will load following the delivery bundles provided by Decision-Maker (DM), where parcels of the close delivery destinations are grouped, and each group is preferred to be loaded in the same space. The DM will select the close (search within 100, 200, and 300 meters progressively) and available parkings for each bundle and routing for the round regarding the selected parkings. After the set of the delivery

sequence of the bundle (parcels) and visiting the sequence of the destinations (route), Kevin leaves the depot to start his round.

When Kevin arrives at the first parking place, his terminal could identify his location and notify him of the order bundles related to this parking place. After he unloads all the parcels and requests the next step, DM will offer him a delivery walking route to reach each order destination. After Kevin delivers all the orders and returns back to the parking place, he will ask DM for the next parking place to be visited until all the parcels have been delivered, and DM will provide him with the route back to the depot.

4.2 Bottom-up modelling approach

Due to the complexity and traits of the city logistics system, a bottom-up modelling approach is adopted in this work. The characteristics of the city logistics system are as follows, each of the component systems is designed and operates independently, such as the Transport Management System (TMS) of various transport operators, and there is no influence on containing system if one of the TMSs fails or is removed. And another advantage of bottom-up modelling is that the initiation of the modelling does not pose a high requirement to the overall understanding of the whole system, so it makes it more simple for multiple stakeholders to have a quick initiation. However, there is also an obvious disadvantage of the bottom-up modelling approach, which is the over-high level of details contributed by heterogeneous stakeholders that can easily cause problems, such as overall incremental effort, difficulty in spotting commonality between related concepts, and risk of inconsistency (Anand, Yang, et al. 2012). The solution we proposed here is first modeling the objects with a graph-based approach. And in the next step, in order to avoid duplicated efforts, we will not build the ontology from the scratch but match the existing ontology with the objects to be modelled to reduce inconsistency and poor interoperability to the most extent.

We start modelling specific objects based on the *Property Graph*. Because CSCL is an IoT environment, where the graph database is recommended to manage the data (Cai et al. 2017), and PG is the meta-data model of the graph database. Likewise, Privat, Bolle, and Raipin-

parvedy (2019) also proposed that PG is the versatile and expressive existing model to describe Cyber-Physical Systems in IoT or WoT environments. Next, graph-based data in PG will be abstracted into an ontology for describing the objects' types and their properties. The overall modelling approach is shown in Figure 15.

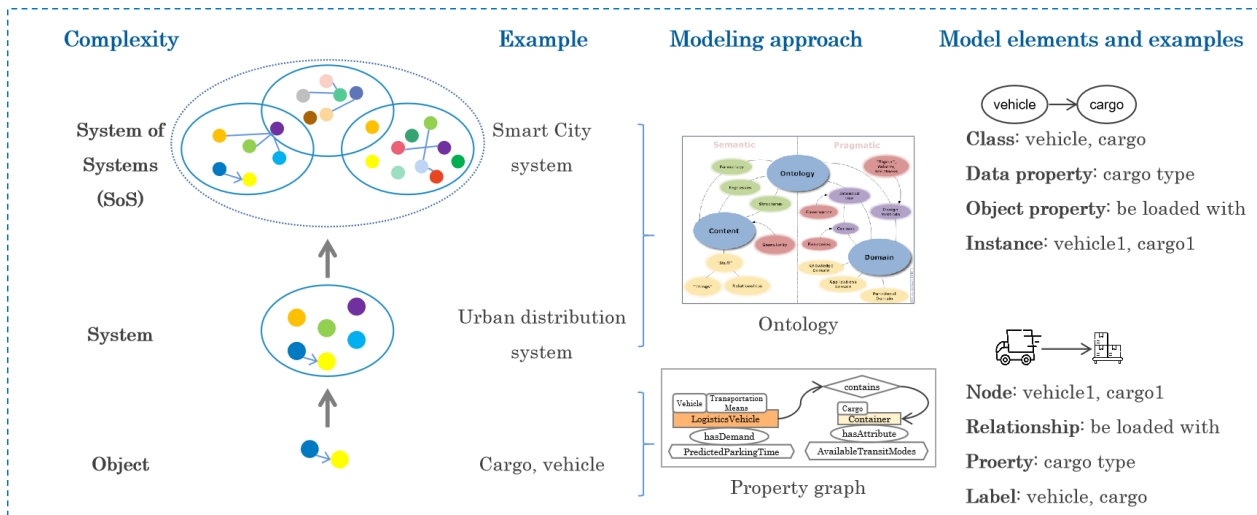


Figure 15. The illustration of the bottom-up modelling approach.

4.3 Property Graph for Bottom-layer modelling

4.3.1 Property Graph: A graph model

Among the objects involved in City Logistics, they are connected with each other and have various complicated relationships. They are not isolated pieces of information but rich, connected domains. These objects include *logistics infrastructure*, such as warehouses, and distribution centers, and types of *transportation means*, such as (electrical/autonomous) vehicles, trains, and cargo bikes, and *logistics goods*, such as parcels, packages, full truckload (FTL) and less-than-truckload (LTL), etc., and *logistics customers*, individuals, companies or governments. We need to clearly show these relationships in order to process and query connections efficiently to support the operations planning.

Property Graph (PG) is one type of graph model to build the basic components of the

graph database, which is ideal for organizing the complex attributes of logistics-related objects and connecting them regarding their relationships. In PG, data is modelled as nodes, relationships, and properties. Nodes represent the graph entities, and they can be described via a number of properties and presented as key-value pairs. Besides, nodes can be tagged with labels, which represent the nodes' belonged classes in a domain. Relationships connect two nodes by a directed and semantic link, and they can also have properties as the nodes do.

We first model a physical object based on the Property Graph (PG) formalism. A PG is a graph model to orderly organizes data or information. It is composed of nodes, labels, properties, and relationships. In a PG, nodes represent the physical entities, and they can hold any number of properties and their values expressed with key-value pairs. Nodes can be tagged with labels, describing their different roles in the domain. Relationships provide directed, named, semantically-relevant connections between two nodes. A relationship has a direction, a type, a start node, and an end node. Like nodes, relationships can also have properties. For example, "loadedWith" has the property "hasTimestamp" (Figure 16). The advantage of a PG is that it is descriptive as it conforms to the human mindset. It originates from Graph Database (GD) technology, and indeed, manages and stores the data in a GD in a way that mirrors the relationships that hold in the real world. As a result, the PG can organize large amounts of complex data, which can later be retrieved and queried by users. Eventually, responses to these queries may be displayed graphically.

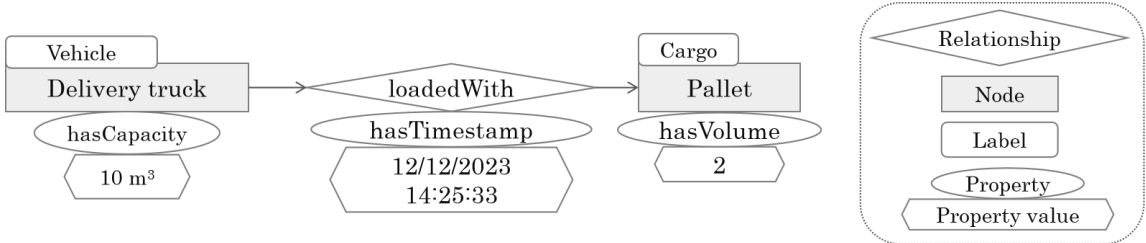
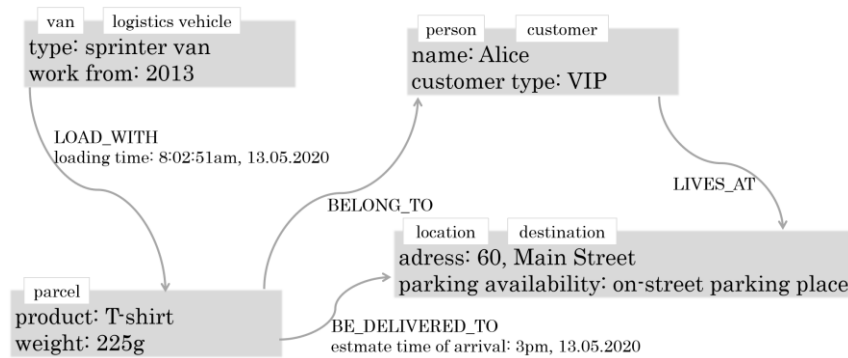
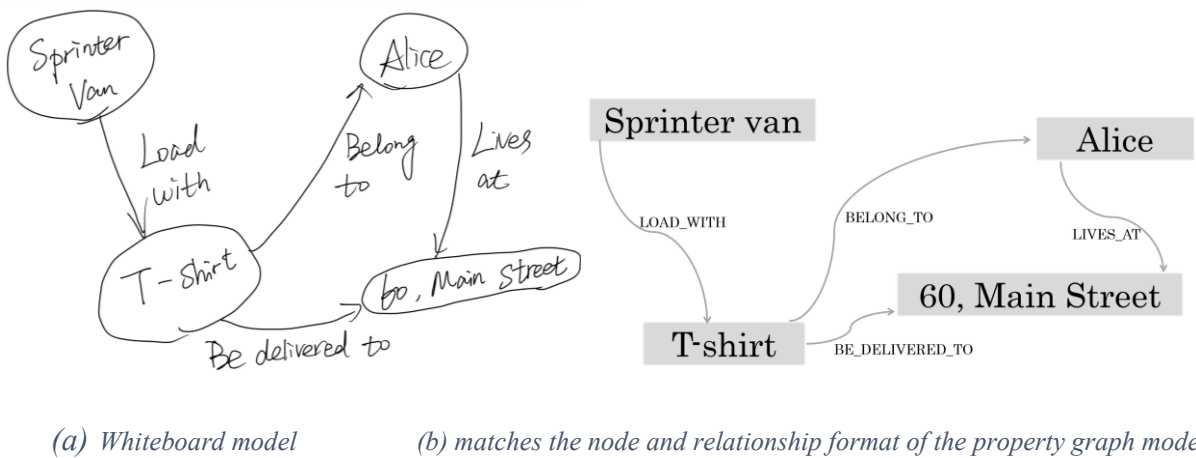


Figure 16. The sensed information of the delivery space state is organized by Property Graph.

This labelled property graph model is very useful for depicting objects and entity-relationship. The advantages of the graph data model are that it is human-friendly because of

its similarity to the human mindset, and also, the relationship-based dataset organization makes it easier for shortest path finding and relevant nodes retrieval from a specific node and regarding its relationships. Figure 17 shows the development of the PG model to describe a city logistics delivery scenario. First, the whiteboard drawing in Figure 17a clearly presents one delivery demand, the vehicle used, and the deliver information. Then, PG will be used to describe the dataset with the elements of nodes and relationships (Figure 17b). Next, the entities will be formalized by labelling the nodes with specific classes and attaching the properties of the relationships to present more operational details of the scenario (Figure 17c).



(c) add labels and properties

Figure 17. Relationship- and property-based graph data model.

Property Graph is very expressive in the IoT and WoT environment. However, since it is developed from practice, the abstract semantics from PG to ontology calls for a transfer. With the help of another graph model approach, the Resource Description Framework (RDF), although it is less expressive than PG, can model the PG stored objects' data with respect to

its standards (Das et al. 2014). Thus, Figure 18 shows us the transfer processes from PG to RDF, and then the objects are expressed with a group of standard conceptual vocabularies. Eventually, with the help of Web Ontology Language (OWL), potent reasoning can be performed to infer new facts based on existing knowledge.

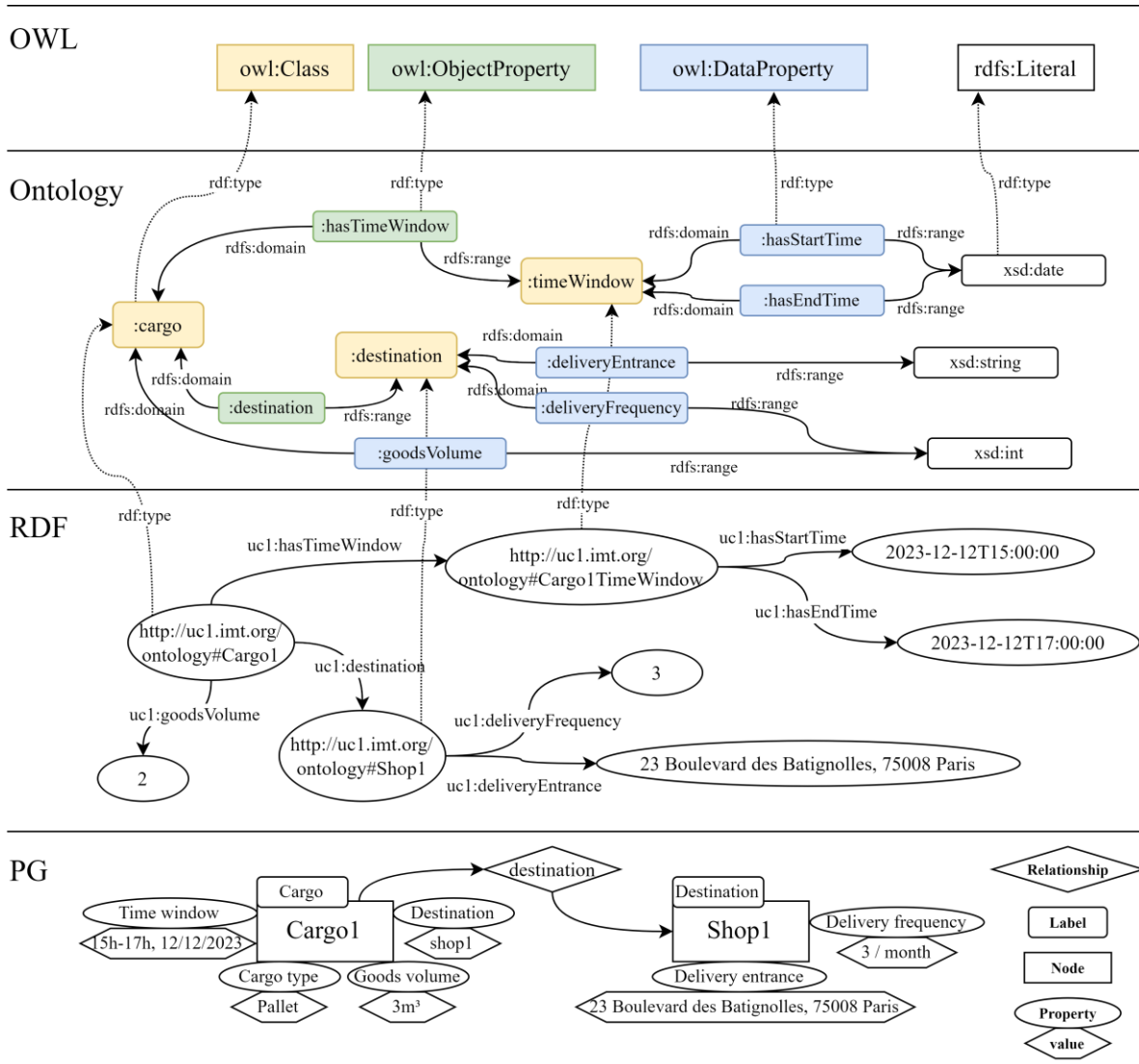


Figure 18. An example of PG-stored DT-related data abstracted into ontology.

4.3.2 Crucial infrastructure categories in city logistics

City Logistics operations and decision-making are very dependent on the information from the urban infrastructure. Last-mile delivery is the most costly part of city logistics, which

accounts for 28% of the total expenses (Wang et al. 2016). Through the analysis of the last-mile delivery and current and potential solutions investigated by the World Economic Forum (2020), the most crucial three categories of infrastructure have been identified and modelled with the help of the graph model, named transportation, parking, and building.

Table 2. State-of-the-art last-mile solution and related crucial infrastructure in City Logistics.

Last-mile solution type	Last-mile solution	Mainly related infrastructure
Secure delivery	Trunk delivery	Delivery space
	Multi-brand parcel shop	Delivery space
Customer movement	Parcel locker	Building
	Office delivery	Building
Last-leg change	Goods tram	Transportation
	Micro-hub	Delivery space
	Retrofitting of parking-based infrastructure	Delivery space
Delivery environment	Dynamic re-routing	Transportation
	Express lane use	Transportation
	Real-time traffic lights	Transportation
	Delivery parking zones	Delivery space
Traditional delivery	Home delivery	Building

Transportation, including road networks and traffic flow dynamics, is a key element of City Logistics and has a significant influence on operational efficiency and sustainability. As shown in Table 12, we figure out the transportation-related last-mile solutions focus more on last-leg change and delivery environment, including goods tram, dynamic route rerouting, express lanes, and real-time traffic lights. Furthermore, we show in Table 8 the factors related to each parking-to-destination solution as well as the City Logistics diagram corresponding to each factor. For example, dynamic rerouting is related to traffic congestion, carbon emissions, parking transshipment, and parking reservation. The traffic factors need to be solved with the traffic system and traffic management system, and the solution is to open a higher priority for the special logistics vehicles that are passing through a crowded area. Without the need to stop and restart the vehicle, they can not only reduce carbon emissions but ensure that the

cumbersome logistics vehicle does not affect the normal driving of the individual cars, thus easing traffic congestion.

Table 3. Last-mile solution factors related to transport infrastructure.

Infrastructure	Last-mile solution	Last-mile solution factors
Transport	Dynamic re-routing	Congestion Carbon emission Transshipment in parking place Change of reserved parking space
	Express lane use	Scheduled parking time Loading freight capacity Logistics vehicle type Electronic signs
	Real-time traffic lights	High-priority access Cargo capacity of logistics vehicles Pedestrian volume
	Goods tram	Transshipment type from parking place to destination Destination of transshipment types covered Delivery time of each transshipment type

Delivery space infrastructure is for the logistics vehicles (un)loading activities near the destination; with vehicles temporarily stopped in the delivery spaces, the unloaded goods will be carried by the deliverymen to the final destinations by walking. However, it showed inefficiency when finding the delivery spaces. Dalla Chiara and Goodchild (2020) show the cruising time for parking takes a portion of 28% of the total delivery time, which causes traffic congestion, urban resources waste, and inefficient logistics distribution. In Table 2, parking infrastructure-related solutions include trunk delivery, multi-brand parcel shop delivery, micro hub, delivery parking zones, and retrofitted parking-based infrastructure. And the solutions factors have been recognized in Table 4.

Table 4. Last-mile solution factors related to delivery space infrastructure.

Infrastructure	Last-mile solution	Last-mile solution factors
Delivery space	Trunk delivery	Parking place of parcel recipient Parking time window Available Logistics Parking Spaces
	Multi-brand parcel shop	Available handling cargo volume Available cargo handling time (parking time) Available Logistics Parking Spaces
	Micro-hub	Available handling cargo volume Available Logistics Parking Spaces Logistics parking vehicle flow rate
	Delivery parking zones	Short-distance delivery parking places Loading / unloading parking places Parcels-delivery parking places FTL / LTL parking places
	Retrofitting of parking-based infrastructure	EV charging parking places Truck parking places van parking places car parking places

The *building* is tightly related to the customers in city logistics, which is the destination of urban delivery. These buildings include office buildings, shopping malls, residential buildings, and so on. Regarding the relationship between buildings and parkings, some types of buildings contain parking lots, like office buildings or shopping malls. Thus, the path to arrive at this kind of parking is needed to be described in the building graph model.

Table 5. Last-mile solution factors related to building infrastructure.

Infrastructure	Last-mile solution	Last-mile solution factors
Building	Parcel locker	Floor location Available space and box capacity
	Office delivery	Office accessibility Alternative destination (Trunk delivery, reception desk)
	Home delivery	Home accessibility Alternative destination (Neighbor's home, smart home steward)

4.3.3 Implementation

4.3.3.1 Use case modelling

By combining the multiple data sources using the Property Graph formalism (Figure 16), we can then model each object, whatever its category. For instance, shops are in the "destination" category (Figure 19), and logistics delivery trucks are in the "vehicle" category (Figure 20).

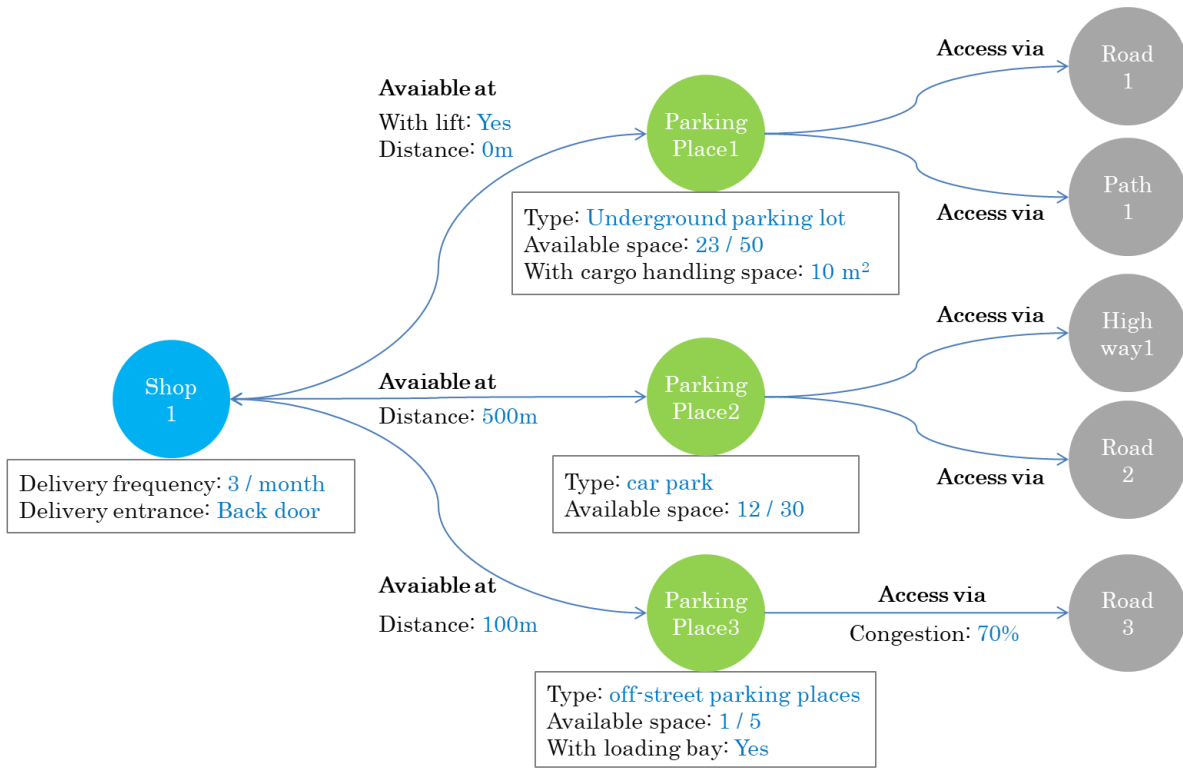


Figure 19. Property Graph organizes data sources from three crucial infrastructure categories.

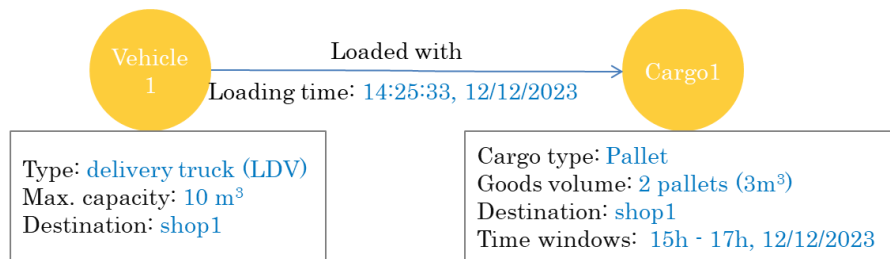


Figure 20. Property Graph organizes data sources from LSPs.

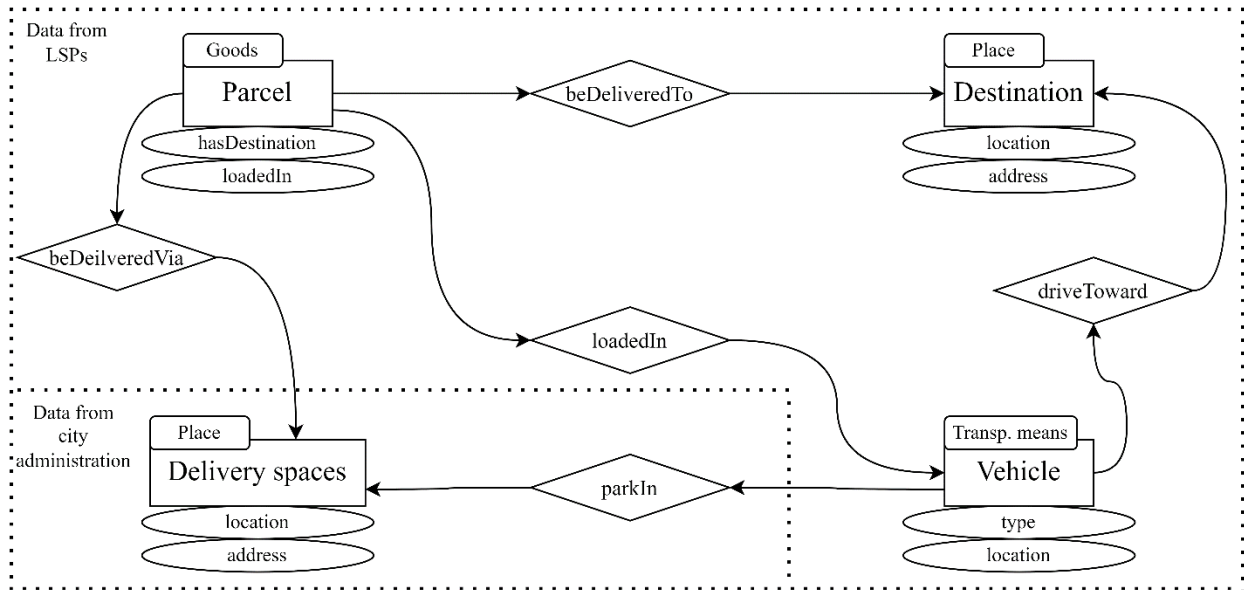


Figure 21. Property Graph organizes data sources from LSPs and city administration.

4.3.3.2 DT management platform

Thing'in is an experimental Digital Twin platform. It provides generic and extensible technological support for the construction of digital twin services. The Thing'in core exposes, through APIs, a graph of digital twins (i.e., a set of nodes and links between nodes). Users can create and manipulate these digital twins and the associated information (function, properties, state, location, shape, etc.), as well as the physical objects to which they are linked (e.g. access to sensors and actuators), but also as above all the structural and semantic relationships between these objects. Thing'in core model is natively property graph and implements the NGSI-LD standard.

Thing'in provides a common informational substrate that homogeneously describes states of the physical world (buildings, factories, cities, roads, and rails...) and therefore allows for the management of digital twins in different and possibly interconnected vertical domains (building, city, manufacturing, transport, etc.). Based on this informational substrate, more complex functions such as simulation or prediction can be developed.

In Figure 22, all the digital twins of the use case are displayed, and the shop is presented in

detail, including information related to itself, like the delivery frequency is three times per month and the address of the delivery entrance. It also indicates the relationship between itself and other digital twins, for instance, connected to parking places via "AvailableAt" (blue arrow), linked to the delivery truck and cargo respectively through the relationship "hasDestination" (orange arrow).

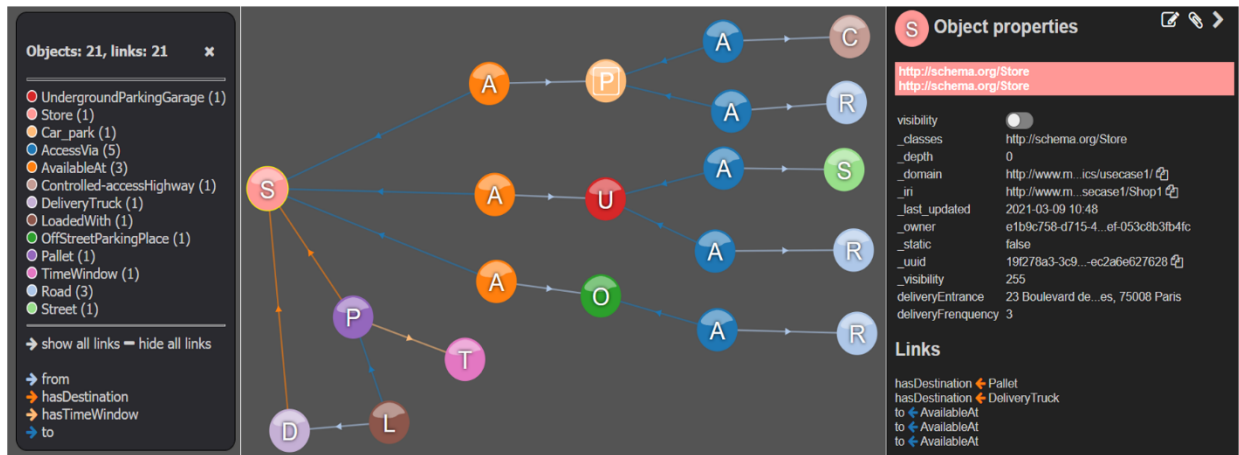


Figure 22. Connected objects (nodes) with relationships (links) and properties (on the right) in Thing'in platform ¹⁹.

4.4 Up-layer modelling – Ontology

4.4.1 Ontology – Enabler for semantic interoperability

In the 1980s, ontology was paid attention to by Artificial Intelligence (AI) researchers. From then on, ontology was introduced into computer science as a technical term. In the 1990s, Neches et al. (1991) proposed ontology as an enabler to facilitate interoperability across multiple, heterogenous databases and systems for knowledge sharing and application. Ontology was defined as a formal, explicit specification of a shared conceptualization (Guarino and Giaretta 1995). In particular, “formal” means ontology must be machine-understandable, “explicit” indicates the concepts and constraints composed in an ontology must be clearly defined, “shared” signifies ontology is not private to some individual but

¹⁹ <https://thinginthefuture.com>

accepted by a group, and “conceptualization” refers to an abstract model of some phenomenon in the world formed by identifying the relevant concepts of that phenomenon (Fensel 2001).

The Semantic Web was coined by Tim Berners Lee, who is the inventor of the World Wide Web to make the internet data machine-readable. The Semantic Web aims to make data understandable and accessible to machines to process data intelligently and discover, compose, and invoke services automatically (Liu and Özsu 2009). Thus, ontology, as the description of the services, formalizes the knowledge for service, meaning capturing and data exchange. Especially, ontology can enhance interoperability between systems since it is an abstraction above the database design. Web Ontology Language (OWL) will be used to define the ontology in a specific domain with the elements of classes, properties, and instances.

4.4.2 Modeling processes

An ontology is a shared vocabulary to represent and define a domain area. It defines concepts and relationships between those concepts World Wide Web Consortium (W3C) in 2021 ²⁰. We used the W3C Web Ontology Language (OWL)²¹ and the tool Protégé²² to design our ontology. OWL allows to define Classes to type an object (e.g. "UndergroundParkingLot"), Data properties to define properties of a Class (e.g. "availableSpace"), and Object Properties to define a relationship between Classes (e.g. "accessVia").

After determining all the objects and their related information, ontology modelling proceeds following these steps (Figure 23): (1) Find the similar classes, object properties, and data properties in the existing and most popular ontologies and catalogs, e.g. the "store," "parking space," etc. from which have been defined in the ontologies like Km4city ²³,

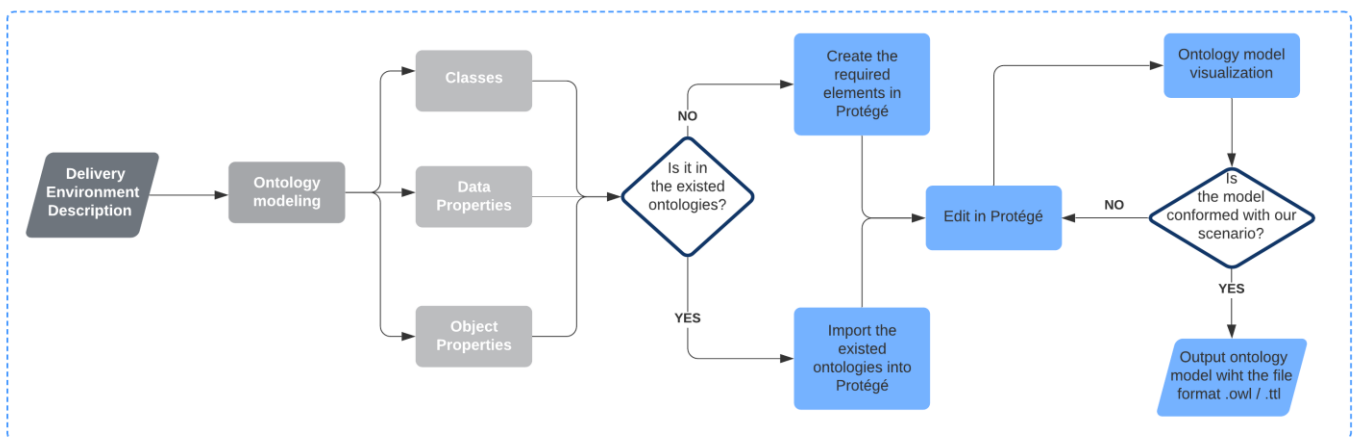
²⁰ <https://www.w3.org/standards/semanticweb/ontology>

²¹ <https://www.w3.org/TR/owl-features/>

²² <https://protege.stanford.edu/>

²³ <http://wlode.disit.org/WLODE/extract?url=http://www.disit.org/km4city/schema>

Schema.Org²⁴, and MobiVoc²⁵. The upper ontology, such as Industrial Ontologies Foundry (IOF)²⁶, is not involved here since the level is too high to find the suitable ontological elements; (2) Import all the ontologies found into the ontology editor Protégé; (3) For the rest of the elements in the model, as we did not find any ontology that provides elements satisfying our need, we create them using Protégé. That was the case for the concepts of "delivery frequency" and "delivery time window"; (4) Double-check the ontology model with a visual display to ensure that the classes and their properties conform with our scenario. Figure 24 shows the ontology model, the classes and their subclasses (the yellow dots nodes),



and the classes come from the existed ontologies are signed with the blue frame.

Figure 23. Working processes in ontology modelling.

Especially, the importance of existing ontology matching needs to be emphasized, which is the key to solving the disadvantage of bottom-up modelling, i.e., overall incremental effort and risks of inconsistency, and also considering face the ontology-perspicuity bottleneck stressed by Hepp (2007). Take an example of the ontology creation of “shop” shown in Figure 19. If we model this object through our limited understanding and further define the classes, range, and restraints, it would not be so supportive for this ontology to be shared and compatible with the existing ontology with the same meaning. Therefore, the approach we adopt here is to compare the objects to be modelled with existing ontology, such as “store”, which has already been described in Schema.org (Table 6); it would be better to use the defined ontology. In this case, it can also benefit from the properties inherited from the parent

²⁴ <https://schema.org/>

²⁵ <https://www.mobivoc.org/>

²⁶ <https://www.industrialontologies.org/supply-chain-wg/>

classes, where the parents of “store” are “Local Business” and “Place”.

Table 6. Partial ontology example of "store" in Schema.org.

Property	Expected type	Description
Properties heritered from parent class: "LocalBusiness"		
openingHours	Text	<p>The general opening hours for a business. Opening hours can be specified as a weekly time range, starting with days, then times per day. Multiple days can be listed with commas ',' separating each day. Day or time ranges are specified using a hyphen '-'.</p> <p>Days are specified using the following two-letter combinations: Mo, Tu, We, Th, Fr, Sa, Su. Times are specified using 24:00 format. For example, 3pm is specified as 15:00, 10am as 10:00. Here is an example: <time itemprop="openingHours" datetime="Tu,Th 16:00-20:00">Tuesdays and Thursdays 4-8pm</time>.</p> <p>If a business is open 7 days a week, then it can be specified as <time itemprop="openingHours" datetime="Mo-Su">Monday through Sunday, all day</time>.</p>
paymentAccepted	Text	Cash, Credit Card, Cryptocurrency, Local Exchange Tradings System, etc.
Properties heritered from parent class: "Place"		
address	PostalAddress or Text	Physical address of the item.
geo	GeoCoordinates or GeoShape	The geo coordinates of the place.

4.4.3 Implementation

4.4.3.1 Use case modelling

The use case will be abstracted into the classes, relevant properties, and restraints. The classes marked with blue frames are matched in the openly shared ontologies, i.e., Shop, Highway, Road, etc. Protégé was used as the ontology editor to create the model.

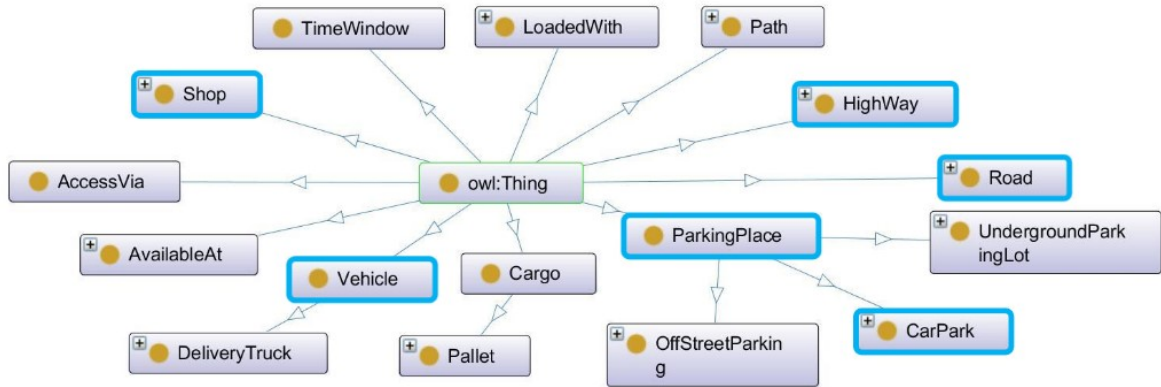


Figure 24. Abstracted classes and relationships of the use case (with existing ontology matching).

Except for the (sub)classes, relationships, and restraints already built, the instances were used to represent objects of the domain of interest. The full model is displayed in Figure 25, where purple diamonds are instances, and the yellow circle is the classes defined in the ontology. Finally, the whole ontology model was shared in the Thing'in platform as digital twins of physical objects and facilities, where it is visible and accessible to other users.

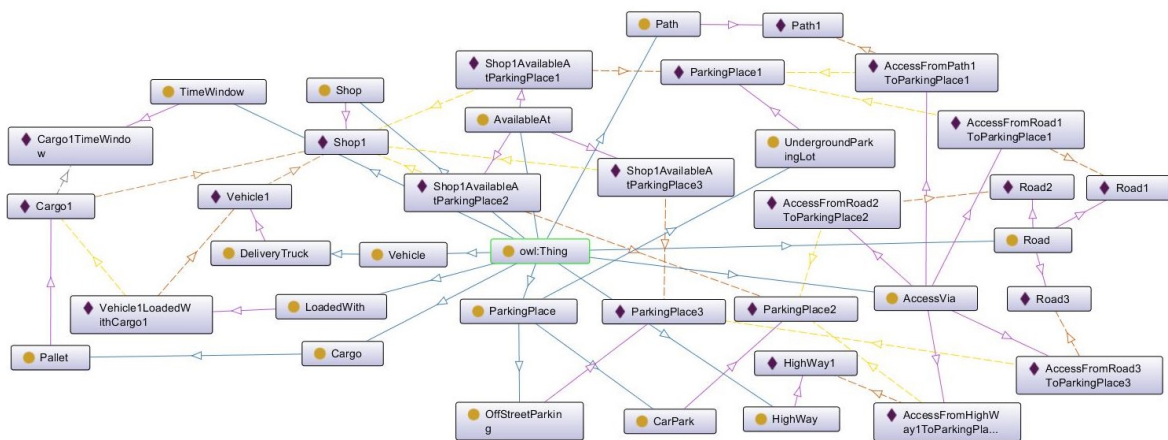


Figure 25. The ontology model injected in Thing'in depicts the physical world of the delivery use case.

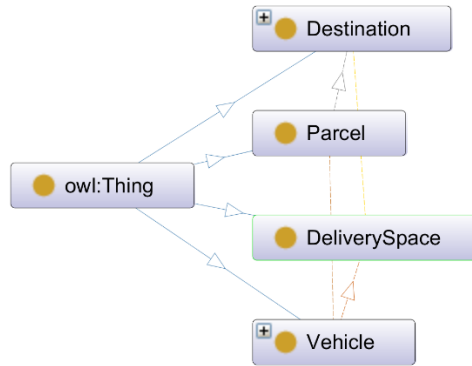


Figure 26. The ontology model injected in Thing'in depicts the physical world of the case of freight parking management in Paris.

4.4.3.2 Reasoning for operations support

SPARQL, a semantic query language, will be used to retrieve semantic data from the open and shared environment that is managed in the Thing'in platform.

Querying suitable delivery space based on cargo type

In this case, the vehicle loaded with the cargo queries to the Thing'in platform for a suitable parking place. It will receive the response of the parking place candidates with sufficient cargo handling space based on the cargo type. For example, if the cargo is only one pallet, the responded parking place should have a loading bay to unload the pallet. When cargo is larger than this scale, more cargo handling space and infrastructure are needed, and the response will provide the specific surface area for the delivery man to check the accessibility. However, the material handling constraints will be weakened for light parcel delivery. An example of the process expressed with Thing'in query language is demonstrated in Figure 27.

Query: My vehicle is driving toward shop1 loaded with a furniture in a size of 70" * 50" * 20", please recommend me with a suitable delivery space within at most 10m from Shop 1?

Respond: For cargo larger than 1 pallet, finding cargo handling space

```
{
  "query": [
    {
      "$domain": "http://www.minesparitech.logistics/usecase1/",
      "$classes": {
        "$any_in": [
          "http://www.minesparitech.logistics#OffStreetParkingPlace",
          "http://schema.mobivoc.org/UndergroundParkingGarage",
          "http://www.disit.org/km4city/schema#Car_park"
        ]
      },
      "http://www.minesparitech.logistics#withCargoHandlingSpace": {
        "$gt": 0.1
      },
      "http://www.opengis.net/gml/pos": {
        "$nearSphere": {
          "$geometry": {
            "type": "Point",
            "coordinates": [
              2.349828,
              48.839863
            ]
          },
          "$maxDistance": 90
        }
      }
    }
  ],
  "view": {}
}
```

For cargo in pallet, finding loading bay

```
{
  "query": [
    {
      "$domain": "http://www.minesparitech.logistics/usecase1/",
      "$classes": {
        "$any_in": [
          "http://www.minesparitech.logistics#OffStreetParkingPlace",
          "http://schema.mobivoc.org/UndergroundParkingGarage",
          "http://www.disit.org/km4city/schema#Car_park"
        ]
      },
      "http://www.minesparitech.logistics#withLoadingBay": true,
      "http://www.opengis.net/gml/pos": {
        "$nearSphere": {
          "$geometry": {
            "type": "Point",
            "coordinates": [
              2.349828,
              48.839863
            ]
          },
          "$maxDistance": 90
        }
      }
    }
  ],
  "view": {}
}
```

Figure 27. Demonstration of the query of delivery space searching based on cargo type.

Querying accessibility of delivery space via a specific road

For the normal cargo type that does not require any handling equipment or spaces, a query can be performed on the distance between delivery spaces and the destinations regarding the connected transportation infrastructure nodes and their properties to find accessible delivery spaces around the destination based on the requests from delivery vehicles. Figure 28 shows the query details.

Query: My delivery vehicle can only pass the specific roads, please recommend accessible parkings for me?

Respond: Accessible parkings that can be accessed via a specific path or roads

```
{
  "query": [
    {
      "$domain": "http://www.minesparistech.logistics/test/",
      "$class": {
        "$in": [
          "http://www.minesparistech.logistics#Store"
        ]
      },
      "<-http://www.minesparistech.logistics#to": "path"
    },
    {
      "$alias": "path",
      "->http://www.minesparistech.logistics#from": "parking"
    },
    {
      "$alias": "parking",
      "$class": {
        "$in": [
          "http://www.minesparistech.logistics#OffStreetParkingPlace",
          "http://schema.mobivoc.org/UndergroundParkingGarage",
          "http://www.disit.org/km4city/schema#Car_park"
        ]
      },
      "http://www.minesparistech.logistics#availableSpace": {
        "$gt": 0
      },
      "<-http://www.minesparistech.logistics#to": "path2"
    }
  ],
  {
    "$alias": "path2",
    "->http://www.minesparistech.logistics#from": "road"
  },
  {
    "$alias": "road"
  },
  "view": {}
}
```

Figure 28. Query accessibility of delivery space via a specific road.

Querying for available or reservable delivery spaces

In the daily delivery, before arriving at the destination or when planning the operation, the availability of delivery spaces is crucial information for operations management. It needs to be noted that if the lead time of planning, for example, if the operation planning performs one hour in advance, then the Estimated Time of Arrival (ETA) needs to be accurate to support the delivery space reservation or the time-changing availability during the one hour.

Query: Available parkings around the destination that can be reserved?

Respond: A number of available or reservable parkings

```
{
  "query": [
    {
      "$domain": "http://www.minesparistech.logistics/test/",
      "$class": {
        "$in": [
          "http://www.minesparistech.logistics#OffStreetParkingPlace",
          "http://schema.mobivoc.org/UndergroundParkingGarage",
          "http://www.disit.org/km4city/schema#Car_park"
        ]
      },
      "http://www.minesparistech.logistics#availableSpace": {
        "$gt": 0
      }
    }
  ],
  "view": {}
}
```

Figure 29. The query for available or reservable delivery spaces.

Querying delivery space within a certain distance for the destination to be delivered

For a given destination or the next destination to be delivered, with a set maximum distance that the deliveryman can walk, the query results will show the available delivery spaces to support the walking delivery.

Query: Closest delivery space around the destination?

Respond: One delivery space with the least distance to the destination

```
{
  "query": {
    "$domain": "http://www.minesparistech.logistics/test/",
    "$class": {
      "$in": [
        "http://www.minesparistech.logistics#OffStreetParkingPlace",
        "http://schema.mobivoc.org/UndergroundParkingGarage",
        "http://www.disit.org/km4city/schema#Car_park"
      ]
    },
    "http://www.opengis.net/gml/pos": {
      "$nearSphere": {
        "$geometry": {
          "type": "Point",
          "coordinates": [
            5.794139,
            45.209853
          ]
        }
      },
      "$maxDistance": 242
    }
  },
  "view": {}
}

{
  "query": [
    {
      "$domain": "http://www.minesparistech.logistics/test/",
      "$class": {
        "$in": [
          "http://www.minesparistech.logistics#Store"
        ]
      },
      "<-http://www.minesparistech.logistics#to": "path"
    },
    {
      "$alias": "path",
      ">-http://www.minesparistech.logistics#from": "parking"
    },
    {
      "$alias": "parking",
      "$class": {
        "$in": [
          "http://www.minesparistech.logistics#OffStreetParkingPlace",
          "http://schema.mobivoc.org/UndergroundParkingGarage",
          "http://www.disit.org/km4city/schema#Car_park"
        ]
      }
    }
  ],
  "view": {}
}
```

Figure 30. Querying delivery space within a certain distance for the destination to be delivered.

4.5 Data injection for freight parking management

4.5.1 Data sources from real practices

A case of freight parking management is conducted to validate the architecture framework and show the operational performance from the LSPs' view, and to access the economic, environmental, and social impacts. In this case, a driver (viz. deliveryman) will deliver parcels from the depot to multiple destinations. The objective is to provide the deliveryman with optimal parking spots and routes to the delivery spaces. A one-day real dataset from an industrial partner is applied, including 166 parcels having 62 destination addresses located in the 17th district of Paris. Moreover, the district has 658 commercial vehicle delivery spaces (the only parking type considered in this work, generally called parking hereinafter) provided by Paris Open Data (Paris Data); part of the dataset has been visualized for presentation (Figure 31). To be more realistic, the delivery spaces located in the surrounding districts and outer boundary cities are also considered, such as the 8th, 16th, and 18th districts in Paris, Levallois-Perret, etc. In total, 3253 delivery spaces are considered for input data, as shown in

Figure 32.

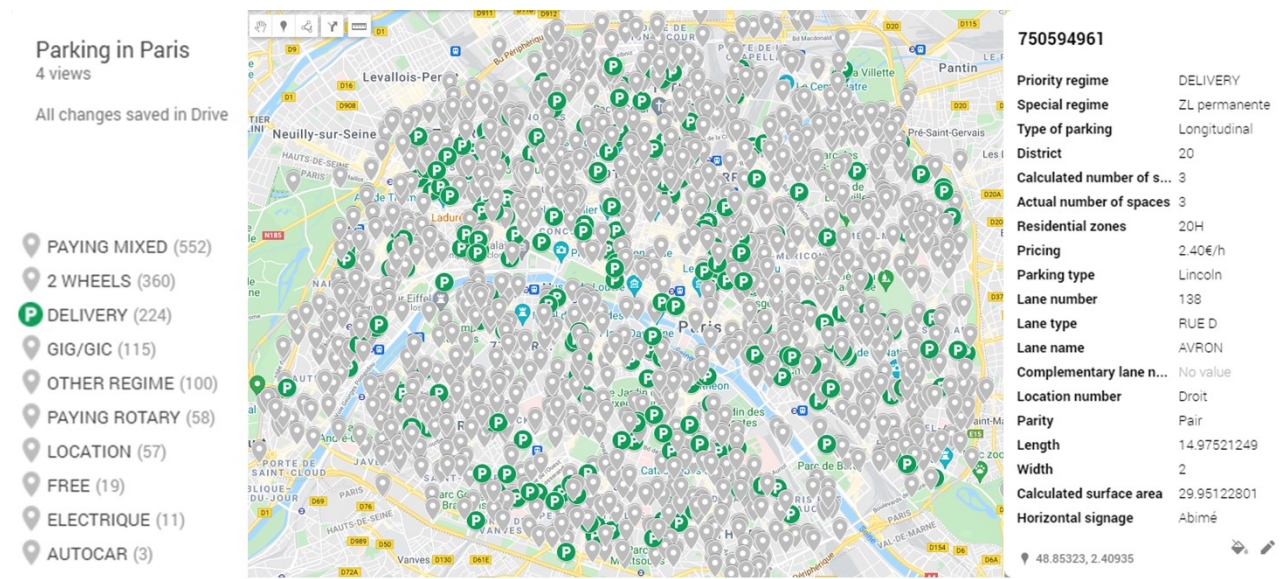


Figure 31. Partial presentation of the delivery spaces dataset in Paris (242 out of 8642 since Google My Maps dataset limit is 1500).

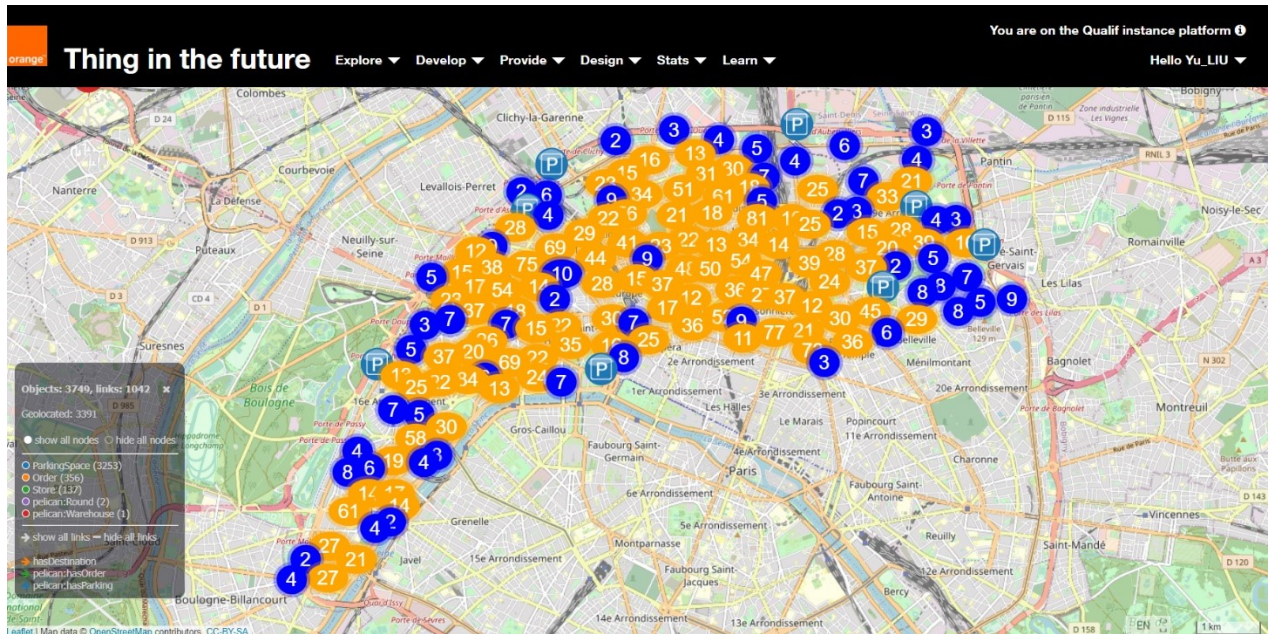
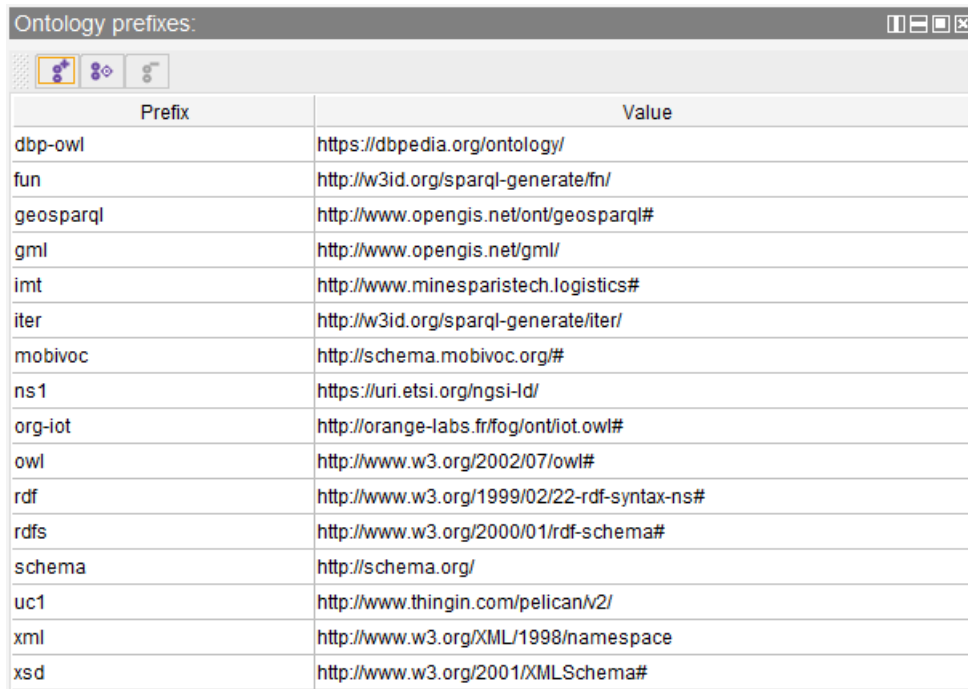


Figure 32. Built ontology shared in Thing'in platform (with accessibility and interoperability).

4.5.2 Built ontology model

Following the ontology modelling processes, it emphasizes matching with existing ontology to increase interoperability and reusability, such as Schema and Mobivoc, as shown in Figure 33. Ontology was built to integrate the data originally siloed in databases of different stakeholders, named LSPs and city municipalities, by describing the relationship between these three classes, i.e., delivery spaces, destinations, and orders. Instances of the ontology, which is a specific object (abstracted from the physical entity) of the class, were created to detail the delivery environment and provide a foundation to respond to the query for the assistance of logistics operations.



Prefix	Value
dbp-owl	https://dbpedia.org/ontology/
fun	http://w3id.org/sparql-generate/fn/
geosparql	http://www.opengis.net/ont/geosparql#
gml	http://www.opengis.net/gml/
imt	http://www.minesparistech.logistics#
iter	http://w3id.org/sparql-generate/iter/
mobivoc	http://schema.mobivoc.org/#
ns1	https://uri.etsi.org/ngsi-ld/
org-iot	http://orange-labs.fr/fog/ont/iot.owl#
owl	http://www.w3.org/2002/07/owl#
rdf	http://www.w3.org/1999/02/22-rdf-syntax-ns#
rdfs	http://www.w3.org/2000/01/rdf-schema#
schema	http://schema.org/
uc1	http://www.thingin.com/pelicanV2/
xml	http://www.w3.org/XML/1998/namespace
xsd	http://www.w3.org/2001/XMLSchema#

Figure 33. Matching with the existing ontology to increase the interoperability and reusability of built ontology.

4.5.3 Semantic interaction and query results

Based on the dataset concerning and connecting the Paris parking data and delivery information, it was injected and shared in Thing'in, which provides open access to other users

for querying and applying. In our case, to support Kevin’s daily delivery of the 166 parcels, the available parkings around the destination (relationship between parkings and destinations) will be queried with the help of semantic query language SPARQL, one query example of parkings around a specific destination will be shown in Figure 34. The query shows us the usable parkings out of 3253 total with a certain radius, i.e., 100, 200, and 300 meters (Table 7). And these query results will be used as input for the simulation-based optimization to support a myriad of deliverymen such as Kevin in the real logistics operation. For example, querying the available delivery spaces within the radius of 100 meters of the destination, 186 delivery spaces out of 3253 have been retrieved and will be used as the input for logistics operations planning simulated by the AnyLogic, an agent-based simulation software (Figure 35).

```

{
  "query": [
    {
      "$domain": "http://www.thingin.com/pelican/v2/",
      "$classes": "http://schema.mobivoc.org/#ParkingSpace",
      "$alias": "parking"
    },
    {
      "$domain": "http://www.thingin.com/pelican/v2/",
      "$iri": "http://www.thingin.com/pelican/v2/adr_104427",
      "$alias": "store",
      "http://www.opengis.net/gml/pos": {
        "$distance": {
          "$alias": "parking",
          "$lte": 200
        }
      }
    }
  ],
  "view": {}
}

```

Figure 34. Query about the delivery spaces around the destination (adr_104427) at a radius of 200 meters.

Table 7. Query results within a radius of 100, 200, and 300 meters.

Radius (m)	Available delivery spaces
100	186
200	476
300	648



Figure 35. Available delivery spaces result from SPARQL query ($r=100m$) from the semantic environment as the input of AnyLogic.

CHAPTER 5 Optimization-based simulation

Résumé

Ce chapitre présente les problèmes de prise de décision et les modèles considérés dans le cas d'utilisation. Sur la base des travaux du chapitre précédent (modélisation des couches 1 à 3), les informations dynamiques souhaitées et utiles peuvent être extraites du réseau sémantique. Ce chapitre montrera comment cette recherche d'informations est importante pour la gestion des opérations dans le cas d'utilisation conçu, la couche dite d'application (couche 4).

Abstract

This chapter presents the decision-making problems and models considered in the use case. Based on the works from the previous chapter (Layer 1-3 modeling), desired and useful dynamic information can be retrieved from the semantic network. This chapter will show how such information retrieving is important for operations management within the use case designed, the so-called application layer (Layer 4).

Logistics Web Applications in *Layer 4* will combine the modelling benefits in the two previous stages. First, dynamic states can be synchronized from the physical to the cyber layer, like the locations of moving vehicles and parcels. Knowledge of the delivery environment, such as available routes and delivery space around destinations, can be obtained from semantic layer 3. So that decisions can be made in the logistics web application based on the dynamics and knowledge. This process will be conducted via optimization modelling and simulation in *AnyLogic*, which is software for agent-based simulation. The sequence diagram in Figure 36 shows the interaction between LSP, *AnyLogic*, and *Thing'in*.

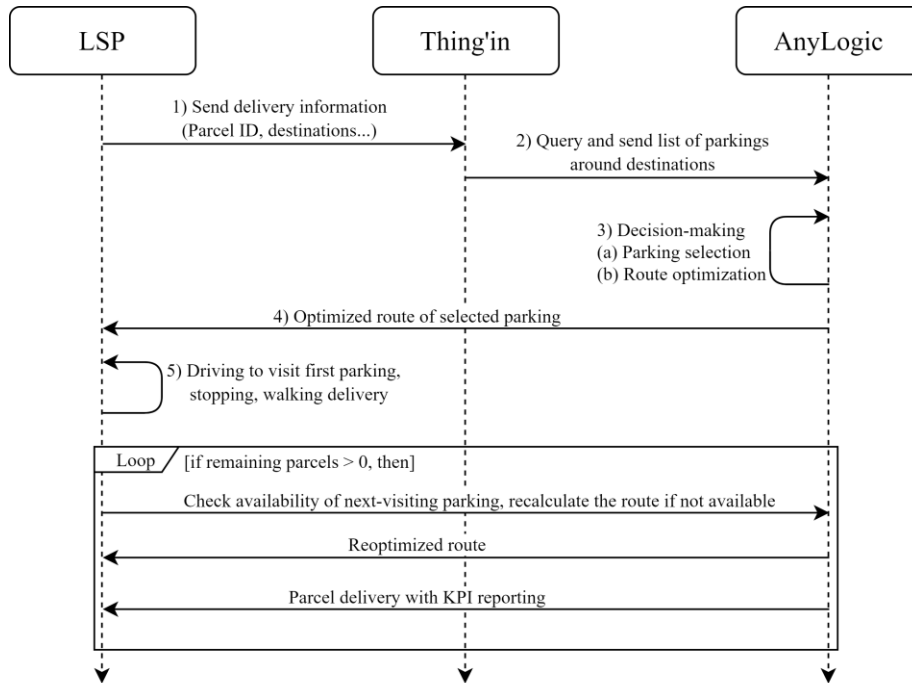


Figure 36. Sequence diagram between operators, DT platform, and decision-making tools.

It should also be specified that the two optimization problems (models and algorithms) are all coded on *AnyLogic*, and no other coding platform or software was used in the study. This is motivated by two reasons. First, the case for demonstration is computationally tractable with *AnyLogic* thanks to the efficient algorithms. Second, *AnyLogic* can be used as agent-based and scenario-based simulation tool, whereby optimizations for decision making can be organized in a step-wise way, i.e., optimization first – simulation second. However, when the size of the case increases, this approach could become a limit of the work.

5.1 Mathematical modelling

Two decisions should be made by the deliveryman based on actual information: parking selection (similar to the assignment problem) and route planning (similar to VRP-Vehicle Routing Problem). A straightforward strategy *parking-first-routing-second* is applied here. Since the related optimization problems are well-studied in the literature and are not the focus

of this work, we adopted well-known modeling approaches and algorithms to solve the problems without making further contributions to them.

5.1.1 Parking selection

It is the process of choosing the best parking places for each parcel from the list of available parking. We adopt the following assumptions regarding the operational environment: (1) An order (a destination address) has only one parcel and it can be assigned to only one parking place (but it could have more than one candidate parking). (2) All orders must be delivered. (3) Some operational constraints are not considered, such as parking capacity or temporal availability (due to the lack of data), and vehicle or deliveryman capacity (since the total number of parcels in the case is reasonable for one vehicle).

The objective of parking selection is to minimize the total number of parking visited (Eq. 1), where p_i is the decision variable of the problem, and $p_i = 1$ if parking i is visited; 0 otherwise (Eq. 4). It is expected that such an objective will have three major outcomes, firstly maximize parcel consolidation per parking to improve last leg efficiency, secondly reduce freight parking land in the city, and thirdly reduce the inefficient cruising time by parking fewer times. Other notations are present as follows: J is the set of orders, each order $j \in J$, and $j = \{1 \dots n\}$; I is the set of parking spaces, each parking $i \in I$, and $i = \{1 \dots k\}$. o_i^j is a binary matrix given by *Thing'in*, i.e., $o_i^j = 1$ means order j can be delivered from parking i ; otherwise, 0 (Eq. 5). The key constraints considered are: i) all orders must be assigned to parking for fulfillment (Eq. 2); ii) only one parking can be chosen for each order to avoid repeated fulfillment (Eq. 3).

Objectives:

$$\min \sum_{i=1}^k p_i \tag{1}$$

s.t.

$$\sum_{i=1}^k \sum_{j=1}^n p_i o_i^j = |J| \quad (2)$$

$$\sum_{i=1}^k p_i o_i^j = 1, \forall j \in J \quad (3)$$

$$p_i = \{0,1\} \quad (4)$$

$$o_i^j = \{0,1\} \quad (5)$$

5.1.2 Routing problem

Upon the list of parking selected, the visiting sequence needs to be decided. The problem can be formulated by VRP models. Since the capacity constraint of the vehicle (or deliveryman) is not considered at this stage, the problem is equivalent to Travelling Salesman Problem (TSP) which is modeled as follows. A set of selected parking are represented by $V = \{1,2, \dots, n-1\}$, plus $\{0\}$ signifying the departure point, so that $V^+ = V \cup \{0\}$, of which the set size is n . All nodes and arcs can be noted in a directed graph $G = (V^+, A)$. Each arc $(i, j) \in A$ is associated with travel distance $d_{ij} > 0$. x_{ij} equals 1 if arc (i, j) is included in any route, otherwise, equals 0. Accordingly, the TSP problem can be formulated by the following integer linear programming model from Miller et al. (1960).

Objectives:

$$\min \sum_{i \in V^+} \sum_{j \in V^+} d_{ij} x_{ij} \quad (6)$$

s.t.:

$$\sum_{j \in V^+} x_{ij} = 1, i \in V \quad (7)$$

$$\sum_{i \in V^+} x_{ij} = 1, j \in V \quad (8)$$

$$u_i + 1 \leq n(1 - x_{ij}) + u_j, 0 \leq u_i, 0 \leq i \neq j \leq n \quad (9)$$

5.2 Solving algorithms

5.2.1 Greedy algorithm for parking selection

The problem of parking selection is formulated as a combinatorial optimization problem that can be efficiently solved by Greedy Algorithm since it has a clear submodular structure and the optimized sub-problem can lead to global optimization (Cormen et al. 2022). In our tailed Greedy Algorithm, the parking that can deliver the most orders will be regarded as the most important and be selected first. The rest of the parking will be chosen following the same rule until all the orders have been assigned. The pseudo-code is presented below.

Algorithm 1 Greedy Algorithm for parking selection optimization

Input: I : a set of parking spaces; J : a set of orders; K : a set of destinations;

L_j^i : a set of orders covered by parking i ; L_k^i : a set of destinations covered by parking;

o_j^i : order j can be delivered via parking i

Output: the selected parking set P

- 1: *Assigned order set* $D = \emptyset$
- 2: *Selected parking set* $P = \emptyset$
- 3: **while** order set $D < J$ **do**
- 4: **for** all parking $i \in I$ **do**
- 5: *delivery capability* c_i of $i \leftarrow \text{count_order}(o_j^i)$ in L_j^i
- 6: **COMPUTE** maximum c_m to find parking m that can deliver most orders
- 7: *remove the furthest destinations in* L_m^k *gradually until to-door time* $\leq 30\text{min}$
- 8: $o_j^m \leftarrow 1, D \leftarrow o_j^m$
- 9: **for** all parking $i \in I, i \neq m$ **do**

```

10:          $o_j^i \leftarrow 0$ 
11:     end for
12:     parking selection set P  $\leftarrow$  parking m
13: end for
14: end while

```

5.2.2 Genetic algorithm for the routing problem

In light of practical applications on large-scale cases, Genetic Algorithm is adopted to solve the VRP problem in this work, as suggested by Tasan and Gen (2012). The initial population is set to 50 feasible routes, with different sequences of chromosomes being the various visiting sequences of the selected parking. Fitness is the driving distance accumulated by visiting the parking in sequence. The crossover probability is set to 0.8 and the mutation probability to 0.2, which are determined after several experimentations. The crossover operator is the Alternating Edges Crossover (AEC). The mutation operators are swap mutation, scramble mutation, and inversion mutation. Iteration will stop when the population evolves to 500 generations, which shows a good trade-off between computing time and acceptable optimal results.

Algorithm 2 Genetic Algorithm for Routing Optimization

Input: R : population of routes; Pb_c : crossover probability;

Pb_m : mutation probability; G : number of generations;

Output: r in R with the shortest delivery distance

1: $GenerationCount = 0$;

2: **while** $GenerationCount < G$ **do**

```

3:   $i = 0$ ;
4:  if  $i < Pb_c * |R|$ 
5:     $offspring = \text{crossover of } (r_i, r_j), r_i, r_j \in R, j \neq i$ ;
6:    insert  $offspring$  into  $R, i ++$ ;
7:  end if
8:   $GenerationCount += 1$ ;
9:   $Rnd = [0, 1]$ ;
10: if  $Rnd < Pb_m$ 
11:    $r_x$  mutated into  $r_x'$ ,  $r_x \in R$  and not the best performed in  $R$ ;
12:   replace  $r_x$  with  $r_x'$  in  $R$ ;
13:    $GenerationCount += 1$ ;
14: end if
15: descend and reduce the extended population to  $|R|$ 
16: select  $r$  in  $R$  with the shortest driving distance
17: end while

```

5.3 Simulation in AnyLogic

5.3.1 Three simulated scenarios

Three scenarios were simulated, as illustrated in Figure 37. In all scenarios, parking information, e.g., the closest candidate parking or those within a radius of each destination, are queried from the *Thing'in* platform, as shown in Table 8. Queried results in the semantic layer as the input for the application layer (a link represents the relationship between objects).. Links here represent the relationships between objects, e.g., a parking-destination link

meaning that the destination can be accessed via the surrounding parking of the link, or a parking-parcel link meaning that a parcel can be delivered from a parking.

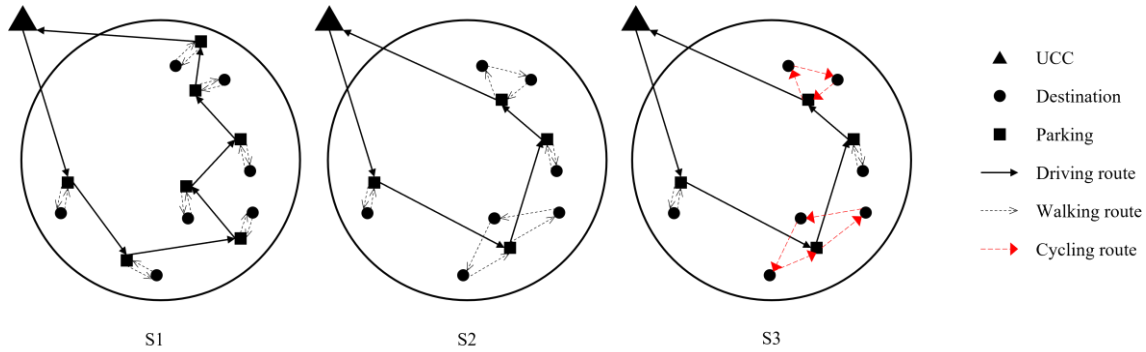


Figure 37. Schematic view of current operations (S1) and two tested scenarios (S2, S3).

S1 of Status-quo scenario simulating the current practices: It is designed that the deliverymen drives from the depot and stops at the closest parking of each parcel's destination address, then walks to the consignees and walks back to the parking for heading to the next stop. Consequently, parcels are not consolidated in this scenario (we recall the assumption that each destination receives only one parcel).

S2 of parcel consolidation: The deliverymen may deliver a bundle of parcels to different destinations from one parking through on-foot routing. We aim to investigate the impact of parking selection on parcel consolidation, that is, the potential to deliver a higher number of parcels during each parking stop within the designated catchment area of the parking facility. Five catchment radius settings have been studied: 100, 150, 200, 250, and 300 meters. 100 meters is calculated upon the dataset, which is the distance to find at least one parking for each destination, whilst 250 meters was suggested by Letnik et al. (2018) as the acceptable walking distance regarding the walking willingness of the deliveryman. However, the experimental results showed that 300m is an interesting turning point in the case study to show the effect of consolidation (see Section 4.2). This is of particular interest for investigating a freight-related regulation in Paris, which is the use of freight parking spaces is free but limited to 30 minutes (Dablanc 2015). Regulatory and environmental insights are

expected from a study of the impact of such a regulation on delivery consolidation, parking occupation time, and land use.

S3 of eco-friendly modality: It is to investigate how our approach can help facilitate a modal shift from vehicle to E-cargo bike at selected parking serving as transit points. This initiative stems from the belief that the increasing volume of consolidated parcels necessitates environmentally friendly solutions for the last meters. It is designed to enable the deliveryman (in a vehicle) to transfer parcels to an E-cargo bike rider at selected parking so that the parcels can be delivered to the door via bike routing. Unlike S1 and S2, S3 involves separate operators for the to-parking leg and the to-door leg. This setup aims to minimize both vehicle waiting time and parking dwell time.

Table 8. Queried results in the semantic layer as the input for the application layer (a link represents the relationship between objects).

Catchment radius (m)	Parking pool	Parking-destination links	Parking-parcel links
100	182	264	665
150	320	588	1498
200	466	1037	2660
250	566	1562	4042
300	647	2267	5966

5.3.2 KPIs and parameter setting

The three scenarios are simulated on *AnyLogic* with actual data, e.g., roads, average speed in the city, parcel delivery information, and parking location (recall that real-time traffic information is not considered in this step). A set of KPIs (Key Performance Indicators) is established from economic, environmental, and social perspectives, which are defined as follows (related parameters are listed in Table 9).

$$E_{CO_2} = \sum d_{to-p} * e_{CO_2} \quad (10)$$

$$D_d = \sum d_{to-p} + \sum d_{to-d} \quad (11)$$

$$C_d = \sum C_{to-p} + \sum C_{to-d} \quad (12)$$

$$C_{to-p} = (C_v + C_l) * t_{to-p} + d_{to-p} * C_{fl} * P_{fl}, \text{ for each parking visited} \quad (13)$$

$$C_{to-d} = (C_v + C_l) * (t_w + t_{op} + t_{ser} * n_p^i), \text{ for each parking visited in S1 \& S2} \quad (14)$$

$$(C_{EC} + C_l) * (\frac{d_{to-d}}{S_{EC}} + t_{op} + t_{ser} * n_p^i) + t_{tsp} * (C_{EC} + 2 * C_l + C_v) < (14) \quad (15)$$

Table 9. Parameters used in the simulation.

Parameter	Notions	Value	Unit
Vehicle rental cost	C_v	13	€/h
Labor cost	C_l	30	€/h
E-cargo bike cost	C_{EC}	11	€/h
Diesel price	P_{fl}	1.83	€/L
Emissions factor	e_{CO_2}	158	g/km
Fuel consumption rate	C_{fl}	0.13	L/km
Picking time per parcel	t_{ser}	0.5	min
Operating time per stop	t_{op}	1	min
Transshipment time	t_{tsp}	3	min
Vehicle speed	S_v	20	km/h
E-cargo bike speed	S_{EC}	10	km/h
Walking speed	S_w	4	km/h

The CO₂ emissions from vehicles are considered as environmental KPI, which equals the multiplication of the total vehicle driving distances (km) from depot to parking d_{to-p} and the unit emission per km e_{CO_2} (Eq. 10). Eq. 11 calculates the total delivery distance D_d which is

the sum of the total vehicle driving distance d_{to-p} and to-door distance d_{to-d} (by foot in S1 & S2, or by E-cargo bike in S3). Distance between points is calculated based on OpenStreetMap provided in *AnyLogic*, and the gap compared to Google Maps is within 2%. The total delivery costs C_d is the sum of the total to-parking cost C_{to-p} and to-door cost C_{to-d} (Eq. 12). For each parking visited, to-parking costs are composed of vehicle usage, labor, and fuel consumption, as shown in Eq.13 in which C_v is hourly van rental cost (IKEA, 2020), C_l hourly labor cost, C_{fl} van's fuel consumption rate (IEA, 2020), and P_{fl} diesel price. The parameters are used for calculating the costs in function of driving time and distance. Differently, in S1 and S2, to-door costs (Eq. 14) are time-based only, including vehicle costs (waiting time at parking) and labor costs due to on-foot delivery time t_w , parking operations time t_{op} , and the parcels picking time (search, scan, unload) computed by time per parcel t_{ser} and the total number of parcels n_p^i at the stop. Especially in S3, it is assumed that transshipment to the E-cargo bike should happen only if it financially outperforms the scheme with driver on-foot routing, which is verified by Eq.15. Here the transshipment time t_{tsp} is set to 3 minutes, including the hand-over and checking time between the driver and E-cargo biker, as well as the loading time to the cargo bike. The speed settings have taken the issues of congestion and safety into account.

5.3.3 Simulation results and key findings

Figure 38 illustrates an example of a simulation scenario (view in *AnyLogic*) of the case with a catchment radius of 150m. The vehicle leaves the depot (on the left-hand side of the map) to visit the selected parking spaces (marked out with red dots) and back to the depot. The blue lines represent only the visiting sequence, as OpenStreetMap in *AnyLogic* is used for calculating the actual distance. On the right-hand side, the dashboard displays the real-time performance of the delivery operations.

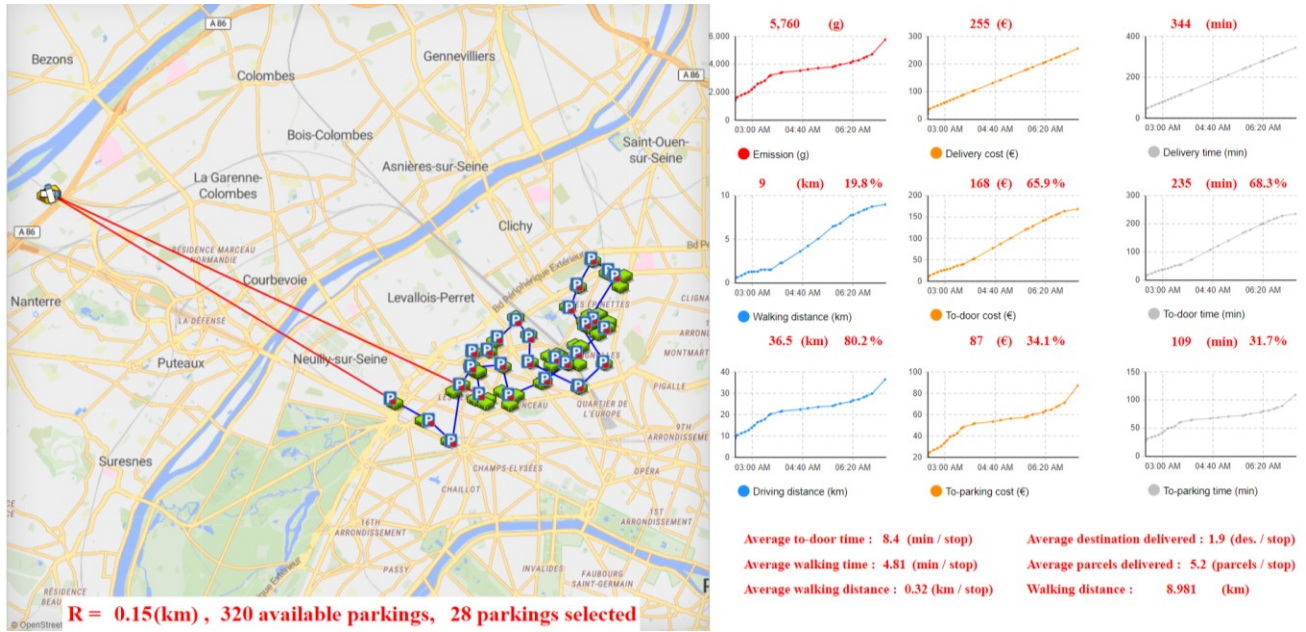


Figure 38. An illustrative example of route planning and performance reporting in AnyLogic.

The simulation results reveal key insights from various aspects of urban delivery schemes. The first is relating to sustainability, considering the influence of freight policies and resource utilization performance. The second is an in-depth operation performance analysis to help LSPs identify key activities to implement these delivery schemes effectively. The third is to dive deeper into the modal shifting, gaining the critical factors to support the adoption of the multi-modal scheme. Quantitative results are detailed in Appendix.

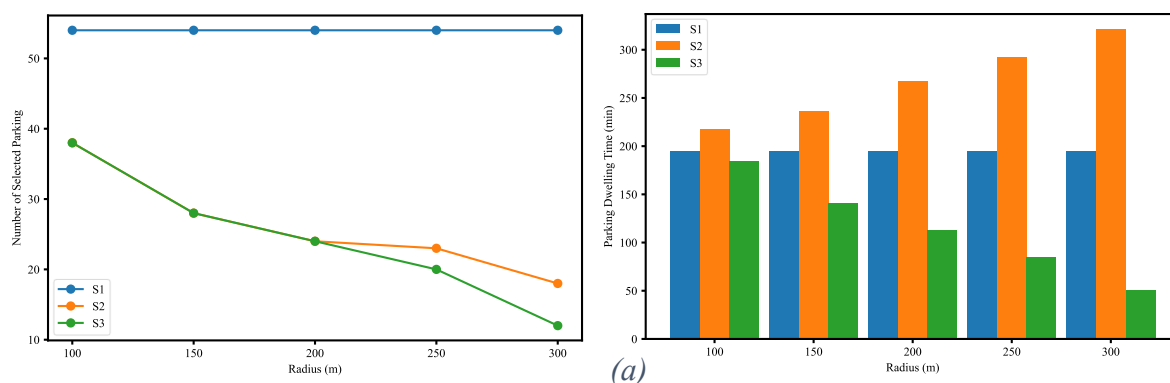
5.3.3.1 Resource utilization

Finding 1.1: Parking demand is significantly reduced because of parcel consolidation, but the reduction is limited by regulations on freight parking utilization.

Compared to S1 with one parking per destination, expanding parking's catchment area in S2 and S3 allows for delivering to multiple destinations from single parking, leading to parking demand reduction. As a result, the number of selected parking shows a compelling contrast, decreasing at least two-thirds in S2 and S3 (Figure 39(a)). The benefits are in various aspects. From the LSPs perspectives, fewer parking searches equate to reduced

inefficient cruising time and costs. Additionally, this advancement yields broader societal benefits such as improved road utilization and reduction of negative externalities, e.g., congestion, pollutions, emissions.

However, S2 also shows the impacts of the freight parking-related regulation in Paris on the consolidation of parcels in single stop, i.e., freight parking duration limited to 30 minutes. Because the number of parcels per stop can easily be constrained by this regulation. Compared to S2, modal shift to cargo-bike in S3 may effectively respect the use time constraint, while resulting in a greater decrease in parking demand, which increases with the increase of radius as shown in Figure 39(a): three and six less parking are needed at the radii of 250m and 300m respectively. The impacts of model shift can be observed apparently on driving distance (Figure 40), emission reduction (Figure 41(a)), and consolidation rate (Figure 12).



The number of parking selected

(b) Parking occupation time

Figure 39. Parking demand and the use time (the constant value of S1 is for illustrative and benchmarking purposes and has no correlation with the catchment radii).

Finding 1.2: Noticeable parking occupation time savings via modal shifting.

This work considers parking occupation time by freight vehicle as an KPI of resource utilization. Although much less parking is needed in S2, the occupation time increases significantly, as shown in Figure 39(b). This results from the extended to-door distances and, therefore, time by walking, which can be intuitively observed in Figure 40. Transitioning to S3, the adoption of E-cargo bikes becomes more time-efficient in parking usage, where parking is used shortly for transshipping. At a radius of 300m, this shift results in nearly 80% parking occupation time-saving, showing a substantial improvement over S1 and S2.

These findings carry profound implications for urban planning and management. Parking demand can be substantially reduced by integrating multi-modality in last-mile delivery and orchestrally operating with time-changing urban resource states. This would contribute significantly to improving urban logistics efficiency, potentially alleviating issues related to parking shortages and parking cruising behaviors.

5.3.3.2 Costs and emissions

Finding 2.1: Less visited parking results in decreased driving distance and emissions.

Figure 40 illustrates the distance travelled by different means: vehicle driving distance, on-foot porter walking distance, and E-cargo biking distance (only in S3). Comparing these three scenarios, it is observed that in a wider catchment area, the driving distance diminishes gradually, saving over 40% distance at most. Emissions shown in Figure 41(a) only consider the part directly generated from vehicles (Scope 1 only), which means E-cargo bike generates no emissions. In S2, when the catchment area becomes larger, emissions decrease by 12% to 35%. Incorporating E-cargo bikes minimizes parking demand, achieving a notable emission reduction of 45% at a 300m radius.

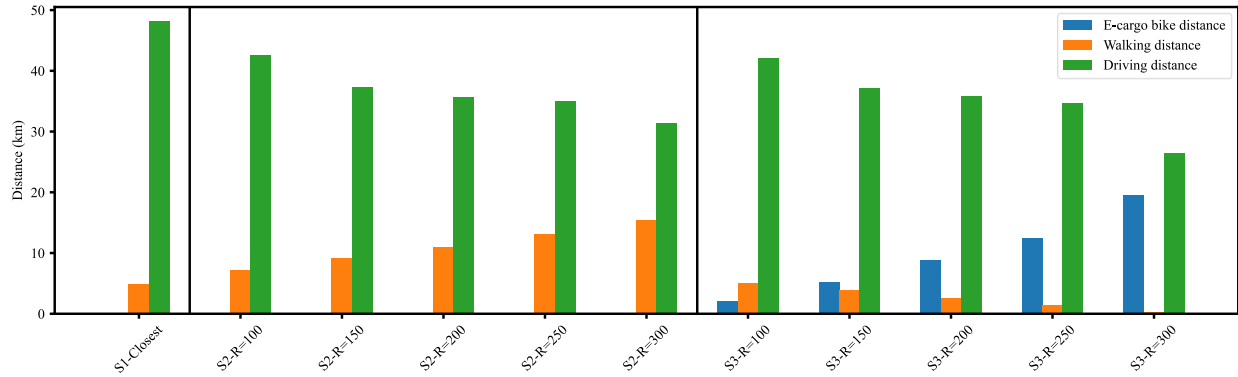
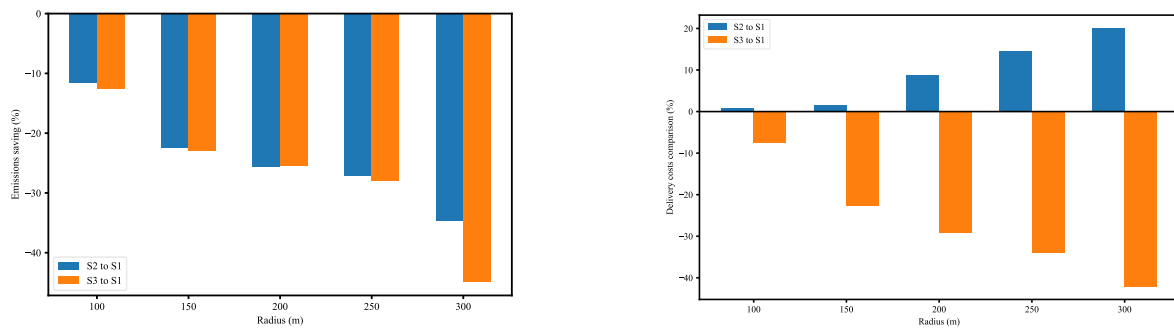


Figure 40. To-parking distance (driving) and To-door distance (on foot or by E-cargo bike).



(a) CO₂ emissions saving

(b) Delivery costs comparison

Figure 41. Emission saving and delivery cost comparison in different catchment radii.

Finding 2.2: As the catchment area enlarges, walking distance stably increases in S2, while it rapidly decreases and replaced by E-cargo bikes in S3.

In S2, larger catchment area leads to stable and obvious growth in walking distance, where drivers perform the to-door delivery on foot. In S3, walking delivery dominates when in a small catchment area since the condition of transshipment has not been satisfied (Eq. 15). As the catchment radius increases, modal shifting becomes more prominent. This trend continues until the radius of 300m, at which point E-cargo bikes take over all the to-door deliveries that need to be handled by leg-work (see Figure 40 and Figure 42).

Finding 2.3: Delivery cost increases in S2 but remarkably decreases in S3 via modal shifting.

Comparing S2 to S1, delivery costs show generally increase as the catchment area enlarges, as shown in Figure 41(b). This rise is due to a longer to-door time, which can be interpreted as increased walking time (labor cost) and vehicle waiting time (vehicle cost). More specifically, the cost changes at radii of 100m and 150m are not significant, which is less than 5%. It is because to-door cost increases and to-parking cost savings are almost offset. However, at a radius of 300m, the to-door cost increase becomes quite pronounced, resulting in a total delivery cost increase of 20%. The result suggests that parcel consolidation via driver delivery can cause a non-linear cost increase, depending on the parcel distribution and the size of the catchment area, so the setting of the catchment radius need to be well considered when adopting this scheme.

When comparing S3 to S1, significant cost savings are apparent, ranging from around 10% to over 40% (see orange bar in Figure 41(b)). Although E-cargo bikes still need to be used as a replacement of vehicle, due to shorter to-door time (results from higher E-cargo bikes' speed), the savings are obvious. In addition, instead of waiting and occupying the parking, vehicles will go towards the next stop after a short transshipment, which is a cost- and time-effective solution regarding operations and resource utilization.

5.3.3.3 Opportunities for modal shift

Finding 3.1: Consolidation rate rises in S2 and S3 while the role of transshipment is increasingly significant in S3.

More parcels are delivered via consolidation at parking as the catchment area becomes larger. At a radius of 300m, the consolidation rate (the number of consolidated parcels to the totality) is only 80% in S2 compared to nearly 100% in S3, which shows the advantages of modal shifting in a large catchment area with respect to use time limit. In S3, as the to-door catchment expands and more parcels are consolidated, modal shifts are adopted more frequently, until take over all consolidated parcels at a radius of 300m.

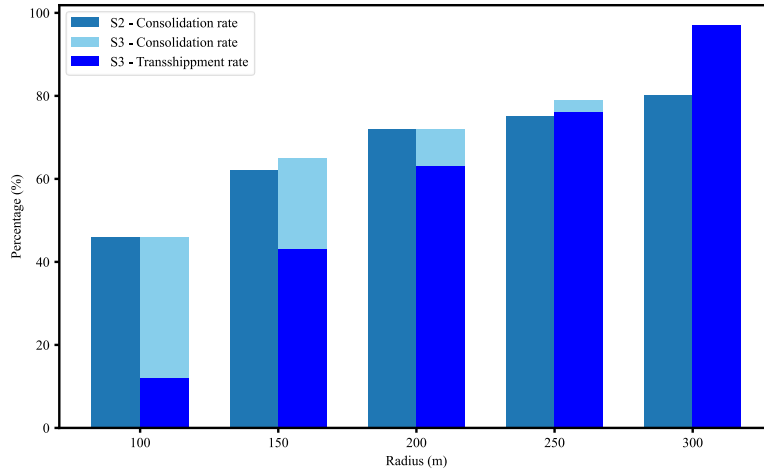
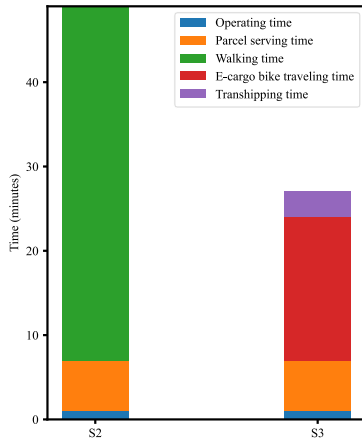


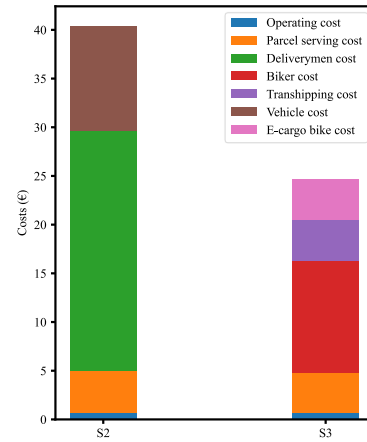
Figure 42. The percentage of consolidated or transshipped parcels.

Finding 3.2: High to-door cost in S2 and noticeable transshipment costs in S3.

Figure 43 shows a detailed breakdown of the to-door time and costs in a selected parking, aimed at providing a clear understanding of the factors contributing to these differences. Two significant insights emerge from this breakdown. First, in S2, it can be observed that more than 80% of the to-door time has been spent on walking, which is nearly double that of cycling in S3 (Figure 43(a)). This is also aligning with the costs shown in Figure 43(b), the cost associated with vehicle use is substantially higher than E-cargo bike costs, more than double. This reflects the low efficiency of walking delivery in such a large catchment area. Second, although the transshipment time (in purple) is not particularly lengthy compared to other operation times, it incurs substantial costs due to the involvement of two vehicles and two delivery personnel during the transshipment. Hence, the way to organize the transiting operations will impact the cost heavily. The dynamic information about the infrastructure and related personnel are key, as emphasized and involved in this work.



(a) To-door time breakdown



(b) To-door cost breakdown

Figure 43. Example of To-door time and costs in a stop having 12 parcels to 5 destinations.

In summary, the breakdown indicates that parking acting as a transshipping point can yield considerable savings, both in terms of parking occupation time and delivery cost, exceeding 40% in both cases. Therefore, S3 exhibits superior performance in terms of both time and cost efficiency, proving to be a promising strategy for last-mile delivery.

5.3.4 Managerial insights

5.3.4.1 City administrators

Freight policy making and evaluation. The delivery space use time limit could be re-evaluated to promote the parcel consolidation effect for emission reduction, but the efficiency of the resource utilization needs to be considered. However, since the number of delivery spaces is still limited, the locations need to be optimized, and the parking time needs to be bounded regarding efficiency.

Data sharing and open data. Increasing the accessibility of various information on delivery spaces and other infrastructure to city logistics stakeholders, synchronizing them timely with their digital twins for further queries and applications, like availability, occupancy, dynamic prices, etc. It aims at increasing timely support to the operations as well

as the reusability of the data to efficiently and effectively utilize the limited and scarce infrastructure.

Urban planning. Providing transition space to LSPs to handle goods and use cargo bikes for the Last 100 Meters delivery. For example, if some of the delivery spaces show great potential for transit parcels, they are crucial to be retrofitted in the urban planning to support goods transshipment. Besides, to reduce the negative effects, evaluating the commercial vehicle parking utilization rate to figure out the inefficiency and give reference to the site selection of transit hubs.

5.3.4.2 Logistics Service Providers

Delivery cost saving. One aspect is profiting from the parcel consolidation effect by visiting a wider area with stopping once, which leads to less delivery space and driving cost savings. Although the total delivery cost did not show much difference, the extra benefit can come from the reduction of cruising time to search for delivery space in the more and more congested mega-cities. Additionally, improving the efficiency of the Last 100 Meters will generate many profits since the to-door cost takes a portion of 70% ~ 90%. For example, shorten the delivery time from the delivery space by transshipment to reduce the vehicle waiting cost. As one research showed that handing out all the parcels to porters and delivering by them instead of driver delivering and vehicle waiting will potentially save 86% in driving distance on some rounds and 69% saving in time (Allen et al. 2018).

Equipment Upgrade. As the radius increases, both walking distance and the holding parcels of deliverymen have increased. Thus, the equipment for hand delivery needs to be well concerned, which has also been stressed in one research on the Last 100 Meter delivery (Lewandowski 2014). For example, a cargo trolley or wheeled bag needs to be designed to ease the working condition of the deliverymen while enhancing delivery efficiency and goods safety.

Policy requirement fulfillment. From the perspective of LSPs, different delivery patterns can be chosen regarding the destined location. For example, to deliver to the Low Emission

Zones (LEZs), the drive-less-walk-more mode can be selected to meet the requirements. The scope of walking delivery can be calculated by simulation in advance to take the most advantage of parcel consolidation and cost savings.

5.3.4.3 Multi-echelon network

Site selection. With the delivery space selection rule shown in this case, the delivery spaces that can deliver most parcels and has more potential to be chosen to reduce the inefficient cruising for parking time; as a result, reducing the urban resource waste and negative effects on the urban area. The selected delivery spaces can be retrofitted as micro-hubs to handle more deliveries. The selected results can provide insights to urban planners, and these locations are also crucial for LSPs to perform transshipment with suitable transport modes or collaborate with each other to benefit more from the parcel consolidation effect.

Transport modes and collaboration. Various means could be considered to finish the delivery from micro-hubs to final destinations, such as traditional cargo bikes, e-cargo bikes, autonomous delivery vehicles (e.g., Nuro - Autonomous Delivery Vehicle²⁷), etc. The modes selection can regard as cost, delivery speed, capacity, and mobility. With these means, the parking time constraint will have no limit to the number of parcels delivered because the vehicle will leave immediately after handing over the parcels. As a result, the vehicle waiting time and cost will reduce, and so as the to-door time and cost.

Mitigating congestion issues. On the one hand, it is better to drive to the micro-hub with parking once than to the final destination with parking more times. The obvious benefits are that driving distance saves along with cruising time to find the parkings (Dalla Chiara and Goodchild 2020). On the other hand, the use of cargo bikes and other green transport do make positive contributions to the environment. But with the smaller capacity, more bikes will be needed to deliver the same amount of cargo, which means it needs to be further evaluated that

²⁷ <https://www.nuro.ai/>

the traffic is being eased or getting busier through the cycling delivery instead of traditional vehicles.

5.4 Conclusion and discussion

The results have validated the semantic interaction (*Layer 3*) can provide useful information (Table 7 and Figure 35) for operational decision-making (*Layer 4*) and business service development direction for LSPs, and generate insights for freight policy evaluation and urban planning for city managers. Regarding more stakeholders, multiple data sources and their various interactions can be involved in the semantics sharing in the federative WoT platform; *Thing'in* as an example here. The application and potential of Cognitive Smart City Logistics (CSCL) can be extended following the technologies and processes were shown in Figure 14, i.e., the architecture framework of CSCL.

CHAPTER 6 Industrial applications, outcomes, and impacts

Résumé

Ce chapitre présente tout d'abord un prototype d'application développé dans le cadre de nos travaux, appelé PELICAN. Il a montré que notre travail peut avoir des effets concrets sur les industries. En combinant les résultats de la mise en œuvre de l'architecture à quatre couches présentée dans le dernier chapitre, nous discuterons ensuite de l'impact à long terme de nos recherches sur l'écosystème logistique urbain, du point de vue de l'économie, de l'environnement, de la société et de l'écosystème logistique urbain dans son ensemble.

Abstract

This chapter will first display an application prototype developed along with our work, named PELICAN. It has shown our work can make concrete effects on industries. Combining the outputting results of the four-layer architecture framework implementation shown in the last chapter, we will then discuss the long-term impact of our research on the city logistics ecosystem, from the perspective of the economy, environment, society, and the city logistics ecosystem as a whole.

6.1 Application prototype – PELICAN

6.1.1 Introduction

PELICAN is a prototype application developed by *Orange Innovation*, based on the proof-of-concept provided by this work. This application aims at aiding the deliverymen firstly find available delivery spaces. And then timely planning the driving route based on the delivery

space availability and Estimated Time of Arrival (ETA) of the vehicle. Finally, navigating the deliverymen in walking delivery regarding the neighborhood distribution.

It works based on Thing'in, which is a graph-based digital twin management platform, to model the structure and the semantics of the physical world. Part of the semantics is handled through ontologies, where data are injected in RDF and stored in a property graph. Using ontologies allows for defining the information (function, properties, state, shape, etc.) associated with the digital twin and its relations with other digital twins and their environment.

6.1.2 Functional design

Based on the designed use case, “one day for deliveryman Kevin,” PELICAN provides solutions to support Kevin’s daily operations. The implementation includes two parts, the back end, and the mobile application.

The back-end data contains delivery spaces and delivery information (destinations, orders). It must be noted that delivery space information comes from the Paris Open Data, which can be regarded as the sharing data from the public sector, and LSPs provide the delivery information. After data injection in Thing'in, it will calculate parking lists around the destinations. In other words, each order related to the destination will also have a parking list, which means the listed delivery spaces can possibly deliver this order. Next, the algorithm will be used to select one parking for each order based on some rules, such as minimizing the stopping times. Additionally, itinerary services will depend on the real-time traffic and the ETA of vehicles to provide and update the driving route from the depot to delivery spaces and between delivery spaces, and the walking route from the delivery spaces to multiple destinations.

In the mobile application, the deliverymen must first log in with the passwords. And selecting the district that they have been assigned. Here, the parcels have been grouped by districts or the destination addresses (part of the district) if the parcel density is large enough. Next, deliverymen will scan all the parcels and load them in the vehicle. Before the

deliverymen start the journey, the delivery map will present all the chosen delivery spaces and the itinerary to visit these delivery spaces. With each stop, the parcel bundle (a couple of parcels that can be delivered via one delivery space) will display in their application, and the walking route to navigate the deliverymen to all final destinations. After this partial trip, this delivery space will be marked in color grey, and the route of the rest of the delivery spaces will be updated referring to the real-time traffic. The interaction between deliverymen and the mobile application will be ended until all the parcels have been delivered.

6.1.3 Prototyping and mock-up

An application prototype has been developed to demonstrate how the approach could be used in a real-case scenario. For this purpose, we use the same dataset as in the simulation. This application is another option for implementing *Layer 4* (Figure 14). It dedicates a mobile application to the delivery man. With this application, the delivery man gets an overview of the round, as shown in Figure 44.

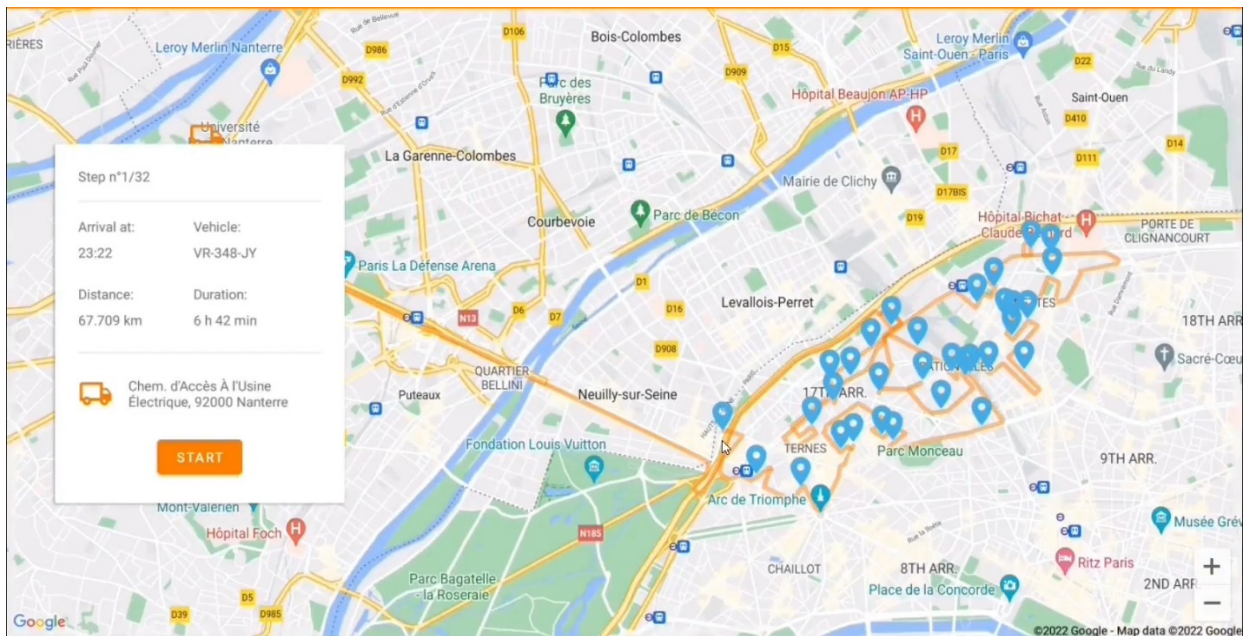


Figure 44. Overview of the round.

In this map, blue markers represent delivery spaces where the delivery man will stop to deliver his parcel bundles (grouped regarding the properties of parcels, such as destinations). This screen also estimates the total distance and the Estimated Time of Arrival (ETA). When the delivery man starts the round, a list of steps is displayed in his mobile application, see Figure 45.

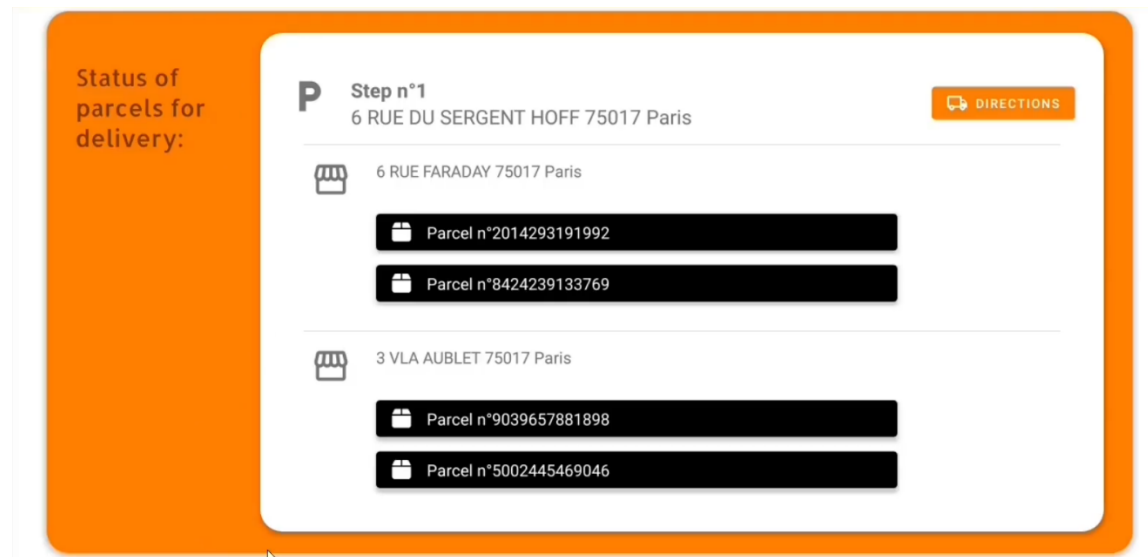


Figure 45. List of steps.

Each step relates to a delivery space and the related destinations of a parcel bundle. Once the delivery man arrives at the delivery space, the application provides a walking route to navigate the deliveryman to the destinations, as shown in Figure 46.

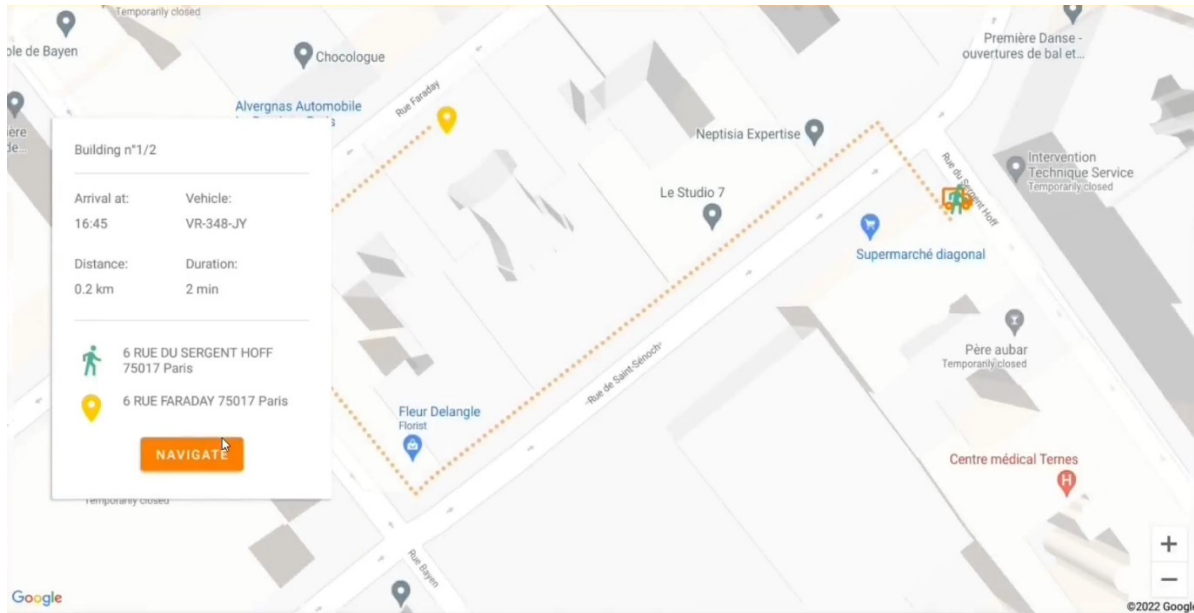


Figure 46. Route for walking delivery.

Once the delivery man arrives at a destination, he scans the parcels to change their status in the Digital Twin from “in delivery” to “delivered” see Figure 47.

Once the delivery man arrives at a destination, he scans the parcels before handing them to the receiver. The parcel status of its Digital Twin will change from “in delivery” to “delivered” (see Fig. 12).

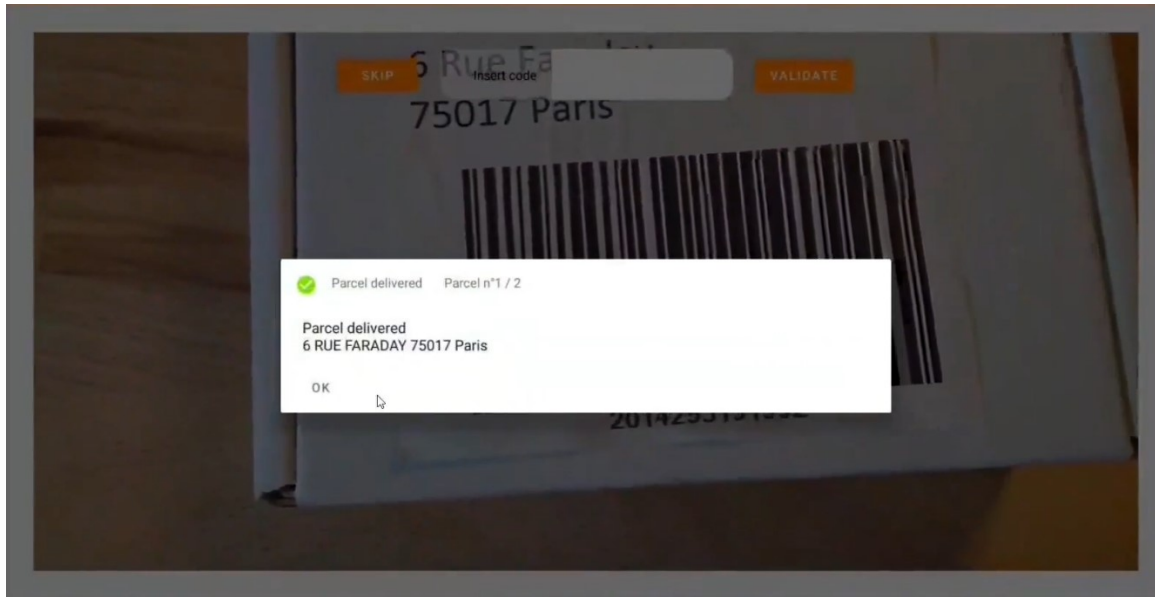


Figure 47. Scanning the barcode of a parcel allows for updating its status.

He delivers all the parcels on foot, following the navigation, and back to the delivery space. Before he heads to the next delivery space, the system can detect if the next delivery space is still available or not. We hypothesize that delivery spaces are equipped with sensors, and the delivery space's availability information is synchronized with the DT of the delivery space. When a delivery space is no longer available, a pop-up alerts the delivery man on the application, and the new delivery space will be selected. At the same time, the route will be recalculated, as shown in Figure 48.

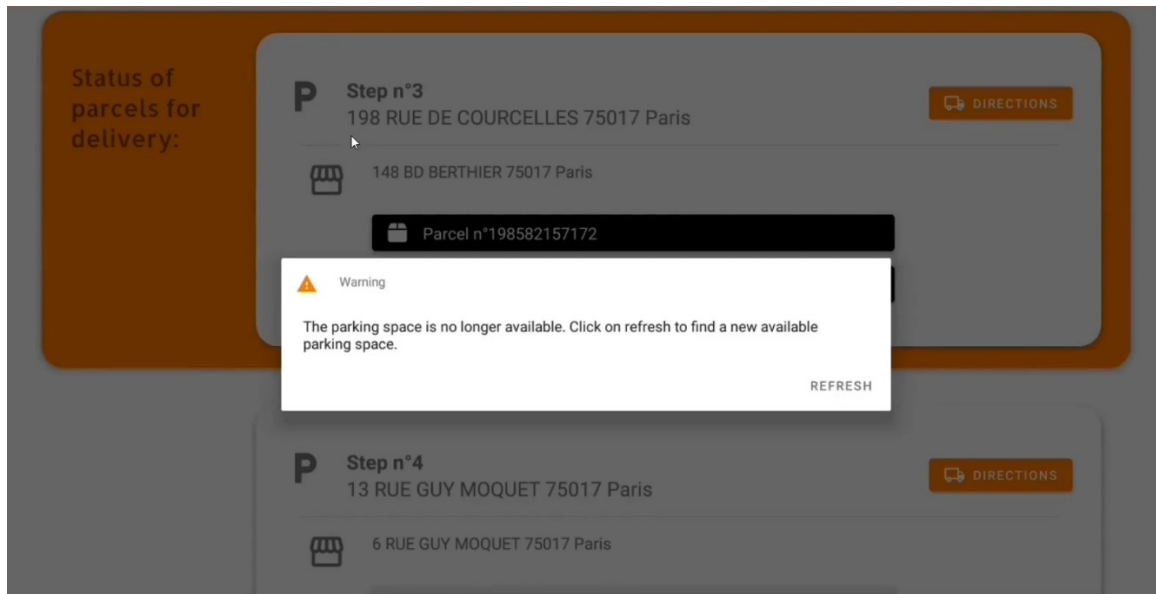


Figure 48. The system alerts the delivery man when the next delivery space is no longer available.

When the delivery man clicks on the “Refresh” button, the system provides another available parking lot to handle the parcels of corresponding destinations. On the other side, the LSP manager can access the dashboard in a web portal, where she can follow the status of the rounds and monitor the delivery performance via a set of KPIs (**Error! Reference source not found.**) once the round is finished (Figure 49). Each grey marker is a parking lot the delivery man has already visited on the map displayed.

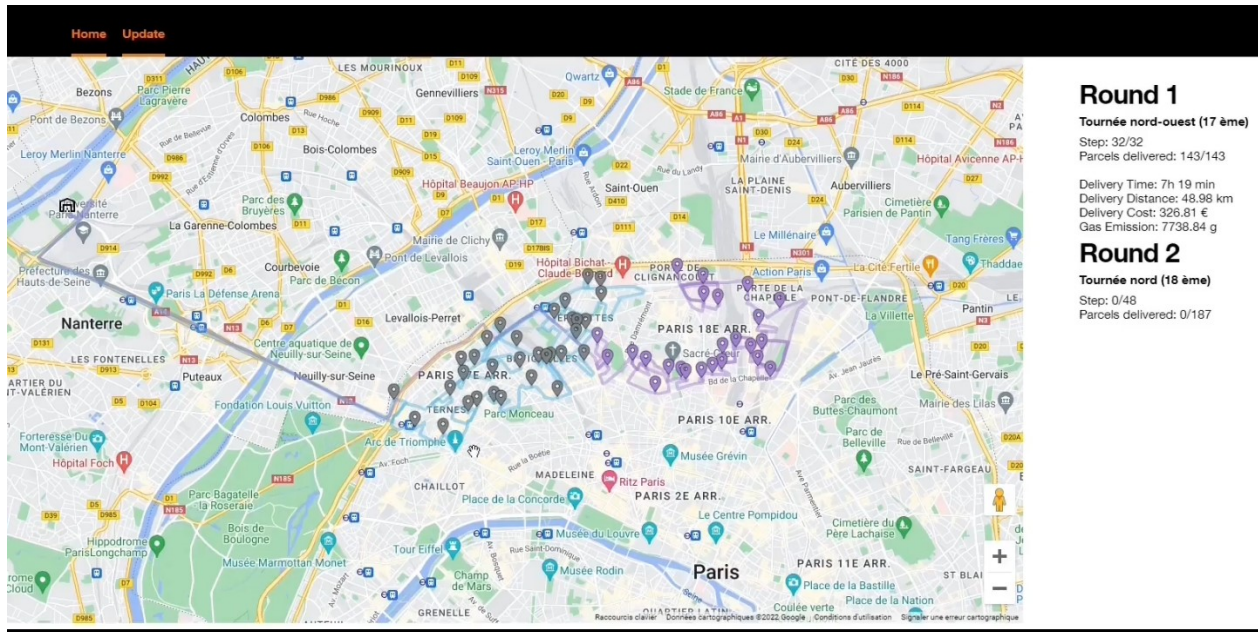


Figure 49. Web portal with the status of the rounds and KPIs.

6.2 Impacts of the Cognitive Smart City Logistics

Cognitive Smart City Logistics (CSCL) aims to share semantic information about objects in an urban delivery environment to make them visible and accessible. This sharing will support stakeholders' collaboration and operations planning, which will have long-term impacts on the city logistics ecosystem.

The first characteristic of CSCL is an “integrated semantic system of city logistics demands, assets, and resources,” which means semantic interoperability is provided to tackle the heterogeneity of stakeholders (database and systems). The advancement of the Internet of Things (IoT) generates the data of the objects' dynamics anywhere, taking us into the age of Big Data. Meanwhile, data are stacked in the silos of segmented IoT applications or platforms for their specific uses. Thus, semantic technologies concentrated on the meaning of the data can connect the data pieces to describe the data itself and the context where they operate. More importantly, data represents the changing operating status and dynamic events. It is ultimately about the logistics-related assets and urban resources, which are objects in essence.

Therefore, semantics was especially used to describe objects' states and the context in which they are operating. It provides interoperability to the heterogeneous stakeholders and helps them create a holistic operational environment where they can straightly share and access the objects. Also, it further provides the platform for stakeholders' cooperation and value creation.

The second characteristic of CSCL, “monitoring and synchronizing the dynamic states of objects,” is to capture the operational performance to support evaluation and planning from a broad view. More precisely, it is to identify timely city logistics demands and available urban resources for supply. Monitoring the operations can provide insight for LSPs to improve efficiencies. It can also offer valuable feedback for city managers to evaluate freight policies. As some former studies have shown, there is a great need to understand various stakeholders' preferences, interaction effects, and reactions to urban freight policies (Stathopoulos, Valeri, and Marcucci 2012; Marcucci et al. 2017). More importantly, the influential and significant impact of CSCL is to identify the logistics demands at that moment and then connect the available and accessible urban resources that can satisfy the needs. For example, when a vehicle suddenly breaks down on the road, it requires a timely response from the services and available resources, the aid services, temporary parking space, and transit vehicles. The responsiveness is related tightly to the connections built between the objects, which are all timely monitoring and synchronizing for decision-making and service providing. As a result, it can directly impact urban resource utilization efficiency and lead to a livable environment.

The third characteristic of CSCL is “autonomous decision-making based on the spatial and temporal status of the assets and resources.” Spatial-temporal values concerning “where” and “when” are used to answer objects' timely availability and accessibility, which are synchronized in their corresponding digital twins. Besides, decision-making depends greatly on the shared and interoperable delivery environment since more supporting information can be provided. Moreover, simulation can be performed to predict the results of potential solutions, which can be used to support cooperation and reaction comprehensively in the dynamic environment. Finally, the made decisions cause the state of digital twins to transform, and DTs will synchronize the state changes to their physical counterparts via actuators, which leads to behavior change in the real world.

6.2.1 Economy

Sharing economy is a socio-economic system where individuals or businesses can share assets or provide services either for payment or free. The sharing objects can be urban infrastructure, assets, resources, and labor (a.k.a. crowdsourcing). Two crucial needs have been shown in the sharing economy for urban logistics transport: real-time information on the shared resources and cost-efficiently retrieving resources and matching needs across platforms and applications. Regarding real-time information, the characteristics of sharing resources are that their shareability is dynamic. In other words, availability, accessibility, and mobility are time-changing. Especially from the view of city logistics, the delivery demands are full of uncertainties, so the lead time to book or use the shared resources is very short, unlike the shared apartments that can be booked one week before or even longer. Therefore, as stressed in the definition of city logistics under the background of crowd logistics, real-time spatial-temporal information is essential to match the crowd-shared services with the logistics demands to aid urban freight transport (Buldeo Rai et al. 2017). Hence, IoT in CSCL can provide the visibility of the available objects via collected sensing data. With the owners' authorization, the objects can be shared, and their information can be displayed on the federative platform.

Meanwhile, the accessibility of the shared objects is enabled for the authorized parties. On the other hand, without synchronization, the resources are allowed to share in different homogenous applications and platforms. However, it is not efficient for both suppliers and consumers. One example observed in practices can be used to illustrate. For crowd-shipping workers, they will be online on multiple platforms at the same time to make the most of their shared time. But if one worker has already been occupied but still shows his availability on another platform, anyone who intends to use this worker's service will fail. So from this aspect, it is not efficient for customers or the logistics operators to search shared resources across multiple applications, particularly sometimes they need to further deal with the price difference. Thus, WoT in CSCL works well, for this reason, integrating the distributed objects into the Web through a set of standard web protocols. It enacts information accuracy about the shared workforce and resources, which is crucial for efficiently and effectively

retrieving. Also, it ensures the objects are controllable in the web control center to assist the resource usage. For example, after the available time slots of a private parking place are announced on the web, a delivery vehicle nearby can reserve the parking to facilitate the last-mile delivery. When the transaction for the sharing is completed, through the operation in the web control center, the red light (actuator) installed in the parking will light up to announce the parking's occupancy, and the parking sensors will monitor the utilization and continuously update the parking's status.

For cost savings, LSPs can improve operations efficiency and collaborate. It is crucial to emphasize two keys to achieve this goal: awareness of the operational environment and enablers to support the interaction between stakeholders for collaboration.

First and foremost, CSCL tackles the “information blindness” about the urban infrastructure, assets, and other resources. This information was originally located in multiple data sources, either stacked in data silos or shared in different encoding formats. CSCL provide LSPs with a federative platform that can greatly increase their understanding of the objects composed in the delivery environment. And it will also assist them in making more reasonable decisions regarding objects to improve efficiencies, such as avoiding temporarily inaccessible streets and being adaptive to traffic congestion or other emergent events. Additionally, it is worth noting that CSCL helps with cost savings in data integration to achieve a holistic awareness of the delivery environment while enabling the small stakeholders to access and contribute to the comprehensive understanding. Traditionally, stakeholders with capital and capability, such as the giant LSPs, integrate data from everywhere to gain the overview to the most extent for the sake of Operations Management. However, the same data source, like real-time traffic information, will be integrated multiple times into different LSPs' systems or databases. Thus, it shows duplicated efforts and resource wastes for multiple stakeholders integrating the overlapping data sources. But their ultimate goal is the same, to understand the status of urban infrastructure. And the undeniable fact is that their data integration helps them build a partial and incomplete understanding of the environment instead of regarding it as a whole. Therefore, in CSCL, the delivery environment is described with a joint effort from each party through the semantic-enabled object's description. Semantic technologies enable this joint description of heterogeneous

partners by providing a group of standard conceptual vocabularies, which are abstracted from but above the design of diversified databases and systems. More importantly, regarding the Small and Medium Enterprises (SMEs) and individual citizens, although they do not have a great capability to integrate data, they do have an accurate understanding of the surroundings and have the resources that can be shared for logistics purposes. Hence, they can contribute to the environment description by sharing information via mobile devices or online platforms or sharing objects by first providing the semantic description on the federative platform. From this perspective, innovative business models are needed to motivate small partners or even individuals to participate in the building of the overall delivery environment. It concerns rewarding the contribution and calls for technological advancement to realize these processes.

Second, CSCL provides LSPs with an enabler for their communication and collaboration. From this perspective, the full-fledged digital twin will be shared in CSCL to find collaborating chances. More importantly, with the simulating capability stressed as a highlight of digital twins (Boschert and Rosen 2016), simulation can be performed with one or a group of digital twins to identify delivery solutions. As an example of cooperation, for one LSP, with parcels delivered gradually, the vehicle is getting empty, i.e., the loading rate is decreasing. With the spatial-temporal states shared by nearby vehicles with high loading rates, CSCL-enabled communication can be conducted between them via query-answering services. Their cooperation and transshipment can save the costs of the low-loading rate vehicle, including the labor cost and the potential external costs of delivering the remaining goods. Besides, as an example of simulation to find the delivery solution, after the ETA of a delivery vehicle is known, solutions of the Last 100 Meters will be simulated to compare the costs of walking delivery and transport mode shift. Specifically, as for the walking delivery, it concerns the walking distance horizontally (calculated in maps) and vertically (computed based on the Digital Twin of the destined building), and the cost for cruising time depending on the dynamic traffic condition, and the possible delay penalty for the forthcoming deliveries, etc. Regarding the mode shift, a simulation will be performed to compare the cost of different modes, including delivery by (electrical) cargo bike and the according labor cost, autonomous delivery vehicles, robots or drones, and possible costs resulting from the surrounding driving environment.

6.2.2 Environment

The comprehensive understanding of the operational environment in CSCL will significantly improve the decision-making quality to save costs and reduce inefficient urban resource utilization and waste. For example, suppose LSPs can be aware of the destination's surroundings and determine whether it is too crowded to support the access of vehicles. In that case, they can find other solutions for the delivery, such as using cargo bikes with the transport mode shift. Thus, the inefficient road utilization and congestion caused by cruising in crowded areas would be avoided, such as 28% of the whole trip time (Dalla Chiara and Goodchild 2020).

The awareness of the delivery environment can help LSPs choose cost-effectively and environment-friendly transport means for delivery. The awareness includes the building distribution in the neighborhood, or more precisely, the internal structure of the building that can provide the parking information and calculate vertical walking distance, and so on. It can significantly improve urban resource utilization to achieve livability and sustainability. Besides, it can also reduce the number of vehicles traveling in the urban area and result in fewer related negative externalities. The possible effects can be seen in project Freight Traffic Control²⁸; seven vans can be replaced by two large vehicles and two on-foot porters or cycle carriers, which can lead to 45% curbside parking time saving, 45% less CO₂, and 33% less NO_x.

The city administration performed freight policy-making and assessment. However, multiple stakeholders interact and influence each other in city logistics, so the importance of considering other stakeholders has been stressed. For example, MacHaris, Tureksin, and Lebeau (2012) emphasized the importance of multiple actors and their objectives in transport project assessment. Anand, Duin, and Tavasszy (2016) use agent-based modeling to understand the interaction between multiple heterogeneous stakeholders in the city logistics domain. Furthermore, city municipalities need the engagement of many private stakeholders,

²⁸ <http://www.ftc2050.com/>

also called participatory policy-making, to assess the policies' feasibility and their effect on behavior change. Thus, Marcucci et al. (2017) proposed participatory urban freight transport policy-making, where the stakeholders' heterogeneous preferences and interaction effects need to be considered.

As for the policy-making in CSCL, with the state monitoring of objects and their interaction, potential operating problems can be identified, and feasible solutions or supporting policies can be provided. For example, if multiple vehicles interact with one available delivery space at the same moment but most of them fail, and the traffic in that area is in a jam, solutions can be found in this dynamic environment. One solution is to collect the prices that LSPs (drivers in the congestion) are willing to pay and make requests with the price proposal to the owners of the connected available private parkings. With their authorization, vans can park nearby for walking delivery, congestion will be mitigated, and idle assets can create value. Additionally, city planners can gain insights from the interacting performance and monitoring of urban resources, such as delivery spaces. For example, they can understand the parkings needed by logistics operations through the interacting frequency between the vehicles and specific parkings. And they can also know the efficiency of parking usage via the occupancy of parkings. Based on these insights, city municipalities can evaluate if it is efficient and sustainable to support logistics operations with the planned delivery spaces.

Regarding the policy assessment before being implemented, one promising feature of CSCL is the simulation capability performed in the shared and interactive environment. It is beneficial for both the public and private sectors. For city administration, they can share the urban infrastructure to improve resource utilization and reduce inefficient logistics operations. On another side, they can gain feedback from the operational performance to improve the policy-making processes. LSPs can share the objects for accessing and interacting with other shared objects, using available urban resources and other LSPs' spare capabilities. As a result, resource utilization and delivery efficiency will be improved. This mutual interaction can provide city administration with more insights from actual practice. LSPs can access the available urban resource and collaborate for more efficient operations and fewer externalities. For example, in our case of freight parking management, the to-door time (i.e., parking time,

including walking time and parcel service time) accounts 76.6% ($r = 100\text{m}$) of the whole trip time. Compared to the operations in the real world, IET (2019) shows that it takes vehicles around 60% of the total journey time to park at the curbside. There is a difference between the simulation results and real practices because of the parameter setting of the simulation. Specifically, walking within a 100-meter radius to deliver from parking to multiple destinations, the radius can be smaller in practice if the deliveryman prefers driving. In addition, the service time for each parcel is two minutes, which can be adjusted based on the workers' experience (familiarity with the neighborhood) and the complexity of the walking delivery, etc. In summary, the simulation results are indicative for both LSPs and city administration, with adjustable parameter settings according to LSPs' special operating conditions and the freight policy for assessment.

6.2.3 Society

CSCL will change how customers participate in city logistics, integrating people's mobility with freight mobility for urban sustainability and livability. People who live in urban areas play multiple roles at the same time. On the one side, they are citizens, and the environmental impact of CSCL can benefit them by reducing externalities. On the other side, they are customers. They have requirements regarding the delivery speed and service level. With the development of digital technologies, customers can also play as temporary delivery personnel simultaneously, working as the occasional driver to deliver online orders on their way (Devari, Nikolaev, and He 2017). However, in this particular crowd-shipping case, the workforce supply is highly dynamic and unpredictable, and the vehicle routing and scheduling problems are significantly different from the traditional studies. The solutions are various. One of them can be at the operational level via operations research to assign the submitted requests and routing to avoid detours and provide the Estimated Time of Arrival (ETA) (Zehtabian, Larsen, and Wøhlk 2022). In CSCL, occasional drivers can share their available time and destined area. LSPs will also share the delivery information containing the destination and time window. Both of the sharing information is spatial-temporal values, and then workforce supply and logistics demands can be matched via the query on the value. After the supply and

demand have been matched, the routing and stopping operation for the occasional drivers can be organized based on timely information about the traffic and available urban infrastructure.

CSCL will upgrade how urban resources are managed and measure social impacts. For example, curb management is crucial for last-mile delivery to handle goods, parking, and walking delivery. The functions of the curb need to be clearly defined to achieve the regulated goal, such as in Paris, there are delivery spaces specifically for logistics purposes. Based on the designed functions in CSCL, timely monitoring and synchronizing can help improve resource utilization efficiency. Specifically, the resource using time will be monitored, while the prediction of social impacts can be made via simulations, and the performance will be shown in the dashboard for city managers' decision-making. For example, by monitoring parking's occupied states in an area, the congestion degree can be predicted based on the simulation. The input information includes the number of delivery vehicles driving toward this area, the remaining available delivery spaces, and the time window of the parcels that are destined in this area, to name a few. With the trade-off between predicted social effects and the current urban resource-using status, other stakeholders can make contributions from their own sides to ease the negative effects. The city manager can choose to provide an exclusive lane for freight traffic, customers can plan a new delivery alternative or time window, and asset owners can share their possessions to help freight movement.

CSCL enhances the allocation of resources and increases the visibility to respond to disruptions. The great needs and possible effects have shown obviously during the COVID-19 pandemic. During the pandemic, populations had been locked down, and the government needed to supply food via delivery. However, it is not available for city municipalities to access the data about urban mobility of goods and freight vehicles (Dablanc 2023), which poses a great challenge for the government to handle the food supply and allocate the resources. As the result of lacking resilience and visibility of city logistics, it will expose the citizens to great risk. For example, in April 2022, Shanghai, the biggest mega-city in China dwelled 25 million people, was locked down. A lockdown of this magnitude puts enormous pressure on government supplies distribution. With the overwhelmed delivery services and the insufficient delivery capacity, goods flow can not be organized efficiently and effectively,

eventually translating to food shortages for the citizens²⁹. From this perspective, CSCL shows the advantages of connecting public and private stakeholders to increase understanding of freight mobility. It will be very supportive of evaluating the social impacts of disruptions to the city logistics system. Additionally, the timely updated utilization of urban infrastructure, the shared assets, and identified workforce will strongly support the resource allocation and innovation of the solutions. For example, voluntary taxi drivers can work as deliverymen during the lockdown, and the delivery personnel in the locked-down area can be identified to increase the delivery capacity. And the buildings not for logistics purposes can be shared and change their role as distribution hubs temporarily to supply the residential area.

6.2.4 City logistics ecosystem

City logistics is an ecosystem where the stakeholders are closely related and influence each other. As the impacts above were shown, the critical stakeholders in city logistics are LSPs and city administrations. Their influencing stakeholders are customers and citizens. LSPs can collaborate with each other to improve operational efficiency and save costs. At the same time, urban infrastructure is crucial to support their operation, so LSPs need to connect and communicate more with the city administration in charge. Eventually, the performance of freight movement will greatly and directly affect the logistics service level of customers and the life quality of urban citizens. So in this part, we discuss how CSCL will change the city logistics ecosystem's stakeholders through resource management, interaction for collaboration, and participation in the city logistics.

First of all, CSCL upgrades the way that stakeholders manage their assets and resources. For LSPs, they have advanced technologies to track and trace their possessed assets, including the fleet of vehicles and logistics facilities. However, the adoption of technologies does help them optimize the operation. Still, this optimization is from a very narrow view, which means they only pay attention to their owned assets to fulfill orders on their side. This independent operation shows great room for improvement, which can be observed from the

²⁹ <https://www.bbc.com/news/world-asia-china-61019975>

very low average loading rate of delivery vans reported by Transport for London, which is approximately 38% (ALICE (Alliance for Logistics Innovation through Collaboration in Europe) 2016). Therefore, CSCL provides a good chance for multiple LSPs to upgrade their current way of managing assets. They can dynamically monitor their assets through the timely synchronization of digital twins from their corresponding counterparts. Then, they can share the operational states of these objects in the federative platform, where the spare capacity of assets is displayed. Next, LSPs can interact with others to access their shared assets based on the logistics demands and operational dynamics. While they are cooperating via sharing owned assets, economic results will be displayed so that it is clear to understand the efficiency of managing and using assets to help them improve operations planning and decision-making. The city administration is responsible for managing the urban infrastructure efficiently and effectively to create a sustainable and livable environment for citizens. Therefore, CSCL assists them in sharing the status of the urban infrastructure, such as occupied or available, with the public for better use. It also helps them monitor the timely usage and aids their analytics of resource utilization, which is very supportive of evaluating freight policies and provides insights into urban planning. CSCL enables citizens to participate in the city logistics operation by sharing their owned assets to support logistics operations or sharing their labor for crowd-shipping. And their contribution will be expressed in either payment or the environmental and social effects they have made. The impacts will be assessed by monitoring assets using or simulating with the digital twins.

Second, CSCL enables the collaboration and cooperation of stakeholders while aiding them in managing the infrastructure and assets from the aspects of participatory decision-making or policy-making. From LSPs' view, they can gain the spare capacity of assets shared by other LSPs, the available urban resources shared by the city administration, and extra delivery capacity shared by crowdsourcing. Then, they can make collaborative decisions based on the dynamic delivery demands and available resources to find the best solution to use these resources in operations. After selecting the resources that will be used, they will communicate with the object owners to access and use the resources. And during the operation, the overall performance of the resource use will be reported via monitoring and simulation. It is conducive to quantifying and qualifying the impacts of urban freight

transport. From the perspective of the city administration, the interaction performed in CSCL between LSPs, urban infrastructure, and the shared resources from the public will provide them with first-hand information to make freight policies and gain insights to support urban planning.

Third, CSCL will promote the development of fifth-party logistics (5PL) as new players in the city logistics ecosystem. 5PL focus on the logistics network instead of one single supply chain that 4PL cares for (Hosie et al. 2012). The emergence of CSCL is to connect logistics-related objects and resources owned by heterogeneous stakeholders. As same as the goal of CSCL, 5PL aims to integrate urban resources highly, and a significant number of city logistics stakeholders will be involved. Thus, the technical service provider is necessary to support the operations of 5PL. The work *Orange* has done during the validation of the framework can be an example of service-providing, which develops freight parking management applications to support urban resources integration and logistics Operations Management. Although our work has proved that multiple stakeholders' shared objects can be integrated into a federative platform, value creation still needs more efforts to innovate services based on the open environment. The technical service providers are essential to enable fifth-party logistics. And more enablers like PELICAN will be developed surrounding this dynamic and shared environment to assist urban resource integration and city logistics operations.

Last, CSCL changed how stakeholders manage the data and objects, transforming them from a closed view of self-management to an open perspective to share and collaborate. For example, a graph database is a human mindset friendly and easy to retrieve, which stakeholders have adopted to manage their data, and indirectly manage their owned assets and resources. However, their management can only involve their owned assets, and they can't gain information about other objects outside, because it is invisible to them without sharing. Thus, the importance has been stressed herein to change the siloed graph data management to semantic-enabled object sharing. Because this sharing is directly and significantly helpful to manage resources and improve operations and resource utilization efficiency. For example, an LSP manages their gained data sources and delivery information in a graph database (Figure 50). On the one side, it does help them to efficiently find parking with a specific

property, such as parking equipped with a forklift (Figure 51). But on the other side, the data about the urban resources they owned is not complete, even though they tried their best to gain data to describe the objects and delivery environment. Thus, with the semantic-based objects shared by heterogenous stakeholders, plenty of full-fledge digital twins will be built to represent their physical counterparts, in order to make better decisions in resource and operations management. More urban resources related to delivery will be shared in this environment, as shown in Figure 52. Based on the open environment, LSPs obtained access to the urban resources to support operations, and city administration can timely understand the urban resource utilization efficiency.

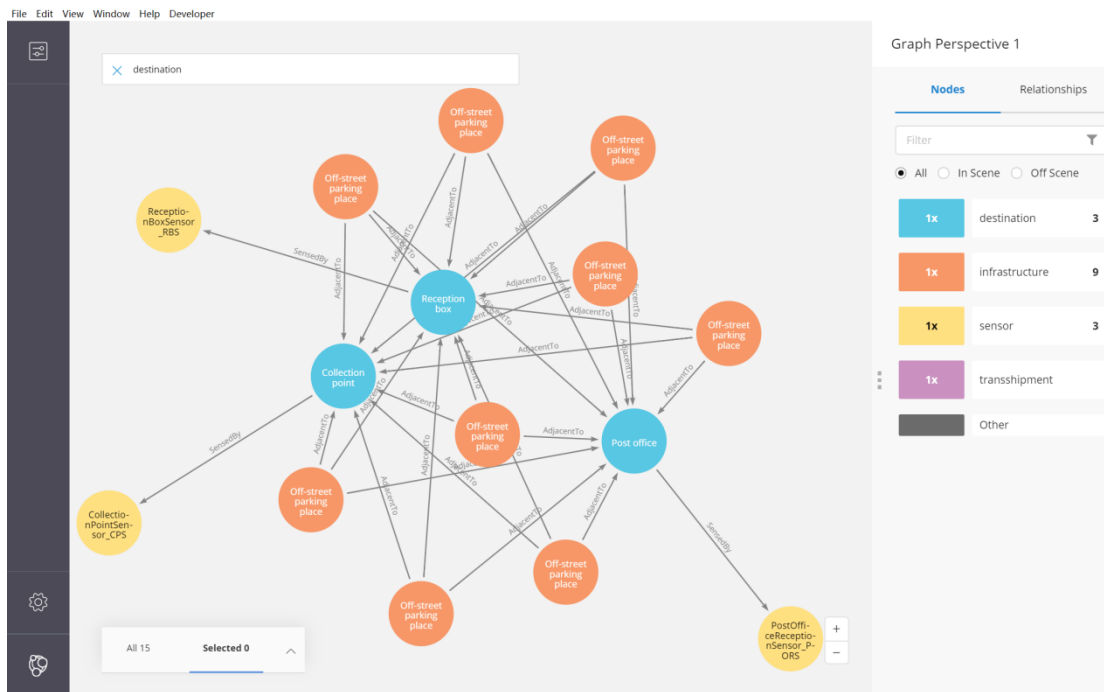


Figure 50. Objects related to delivery and the related urban resources are managed in the siloed graph database.

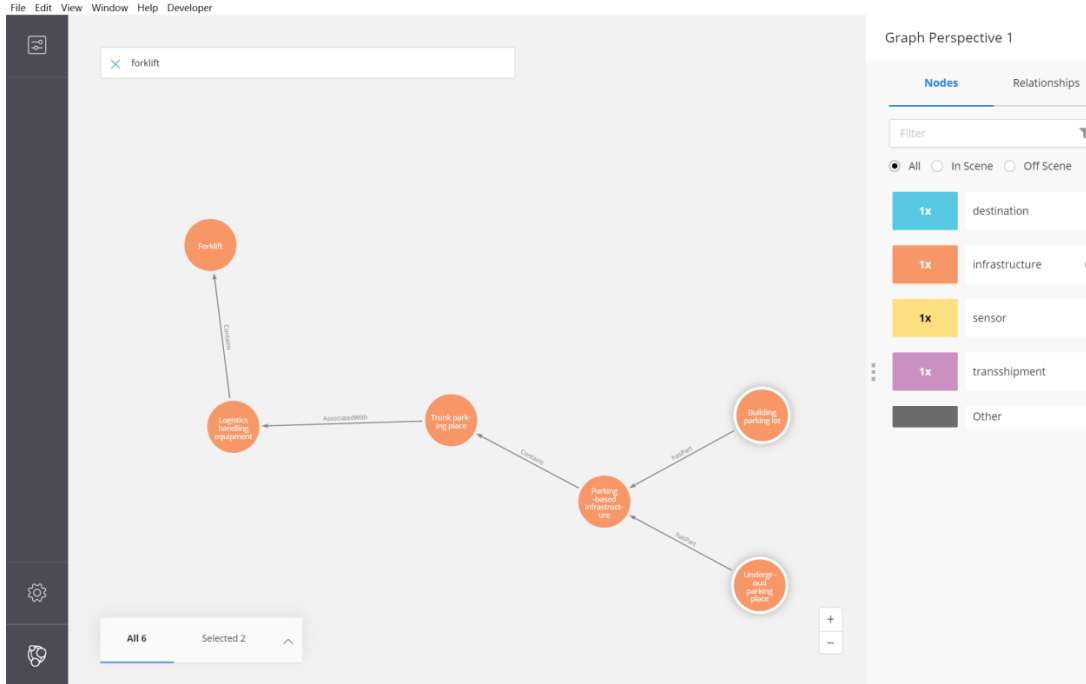


Figure 51. Expand the relationships of “forklift” to find the available parking lots.



Figure 52. The delivery destination and the surrounding urban resources are shared in the federative DT management platform.

CHAPTER 7 Conclusions and perspectives

Résumé

Après avoir validé la faisabilité des technologies numériques, c'est-à-dire les jumeaux numériques et les technologies sémantiques, nous avons constaté des différences positives dans les opérations de logistique urbaine et nous avons examiné en détail les incidences à long terme. Dans ce chapitre, nous illustrerons la contribution de cette recherche, notamment en soulignant les méthodes, la difficulté du problème que nous essayons de traiter et les effets de l'approche que nous proposons. Enfin, nous suggérerons quelques directions de recherche prometteuses et préciserons les limites de notre travail afin de soutenir les études à venir.

Abstract

After validating the feasibility of the digital technologies, i.e., digital twins and semantic technologies can make positive differences in city logistics operations and we have discussed the long-term impacts in detail. In this chapter, we will illustrate the contribution of this research, including highlighting the methods, the toughness of the issue we try to handle, and the effects made by our proposed approach. Finally, some promising research directions will be suggested and the limits of our work will also be clarified to support the coming studies.

7.1 Contributions of the thesis

This thesis explores how semantic technologies and digital twins can work for integrating heterogeneous stakeholders and their owned assets, which further supports resource allocation and operations management. The main contribution is presented in three aspects: changing the operation-supporting perspective from data to Digital Twins (DTs), providing interoperability to integrate heterogeneous stakeholders, propose innovative services to test

the feasibility of CDTs to enable the cooperation of multiple stakeholders for operations management.

7.1.1 From data-driven to Digital Twin-driven operations management

Operations in logistics and supply chain management benefit a lot from data management and analytics. Especially with the development of technologies, the capability of data collection, processing, transferring, and analyzing becomes potent, which takes us into a Big Data age, i.e., the data exists anywhere and anytime. However, the advancement of the Internet of Things (IoT) changes our view from data to “things”. It means the information describing the states of objects that are hidden behind data is more important for operations management, and this information will further aid in using these physical objects in actual logistics activities. Thus, Digital Twin (DT), converged the virtual and physical spaces, is supportive to mirror the information about the object states in the cyber world and perform reaction to the physical world. The information can be handled by the monitoring and synchronizing functionalities of digital twins. The reaction is concerning how operators can use these objects, which depends on the decision-making, i.e., prediction and prescription, processed with the simulation of digital twins.

Digital twins are based on data but are more advanced than it. DT cares about the objects, including their dynamic states and the relationships between them. Data provide insights to support decision-making or operations planning by analytics, while DT performs real-time decision-making regarding the dynamic environment, i.e., the time-changing states of objects as well as their inner relationships. The city logistics operating environment is complex, the urban resources are scarce and their availability is highly unpredictable. Therefore, DT-driven real-time decision-making will greatly improve the decision quality and provide more powerful support to operations. Besides, the strength of DT showcases in simulation capability to assess various problem solutions. Based on the dynamic properties and attributes of objects, and also their relationships, simulation outputs show the outcome and impact of these solutions. The proposed DT-driven decision-making framework demonstrates the potential of insights for managers in prediction and prescription.

7.1.2 Heterogeneous stakeholders integration via semantic interoperability

Our work validated that interoperability can be provided to heterogeneous stakeholders via semantic technologies. It aims at helping them abstract their self-owned systems or databases, which enables sharing, coordination and achieving value co-creation. More importantly, digital twins of objects are the target of semantic abstraction, i.e., digital representation of organized objects' state data, instead of raw sensing data. Thus, it is more convenient to share knowledge about the objects and cooperate based on this sharing. Besides, another advantage of semantics is that it helps with building the “context” based on the consistency provided by the standard conceptual vocabulary. Specifically, stakeholders make their individually owned objects visible by semantic-enabled sharing, which further promotes the awareness of a more complete operating environment. On the one hand, it can directly provide the stakeholders with operating decision-making support. Simultaneously, the comprehensive understanding help the individual objects understand the environment they are operating in, thus, it is beneficial for developing the intelligence of objects and their CDTs. Herein, we have proved that when the delivery vehicle can be aware of the surrounding objects (available delivery spaces), their resource-searching time will significantly decrease, i.e., the cruising time in this case. It will reduce the operational costs to find the available resources or illegal double lane parking, and crucially reduce the externalities generated by these inefficient behaviors. On the other side, since the reserving time is closer to the actual using time, a.k.a. last-minute booking, the users can offer more accurate time slots to other users of the urban resources. It will greatly reduce the high uncertainty produced by reservation in advance, and reduce the idle and waste of the booked resources, which will be very friendly to urban sustainability.

In summary, semantic-enabled integration of stakeholders can provide each of them with real-time knowledge that they can hardly obtain by themselves across heterogenous systems, which can help them gain the resource information to support operations and get more insights to make decisions. As a result, this integration can produce profits in operations and generate benefits for the public. For example, in our studied case, LSP gets real-time knowledge about the delivery spaces, which helps them to perform urban delivery and

operations more versatile and efficiently. And from the dynamic operations states, city administration gains first-hand feedback about the effectiveness of their implemented freight policies through the actual utilization of the resources. It will be very supportive to improve the policy-making or communication and interaction with operators. In this case, they can better fulfill the responsibility to the society and environment in a more effective way. It is predictable that with more and more stakeholders participating in the semantic-enabled sharing, each of them can gain more benefits, and more close-related cooperation can be developed during such a positive circulation based on facts.

7.1.3 Service innovation for coordination, cooperation, and value co-creation

The freight parking issue was chosen as a use case because this problem is so challenging that many researchers have studied it to find solutions (Jaller, Holguín-Veras, and Hodge 2013; Wise et al. 2019; Martinez-Sykora et al. 2020; Muriel et al. 2022). But current solutions have still shown some gaps. For example, Martinez-Sykora et al. (2020) proposed an algorithm to realize the two-echelon delivery combined driving and walking. It can work well to deal with a small number of parcels, but shows the limitation when the number of customers reach a certain small scale. Because with the number of customers and parcels increasing, the growing constraints, such as the capacity of the deliverymen and the walking routes, will exponentially increase the complexity of the combinatorial problem. However in practice it is more important to adapt to an evolving environment rather than seeking an optimal theoretical solution.

Under this background, the importance and feasibility of CDTs in operations management is evaluated. Specifically, we provided freight parking management service with the combination of the most common driving and walking delivery. First, digital twins of LSP-possessed objects, including destinations and parcels, will be built and managed in a platform named Thing'in. In particular, with ontologies enhancement, they work as CDTs equipped with semantic interoperability. Next, via semantics-enabled object sharing by heterogeneous stakeholders, the operating context will be displayed in more precise details, which will be

more supportive for operations management. In other words, delivery spaces are not owned by LSPs but they are shared by the city administration, specifically referring to the city hall of Paris herein. Based on the operational performance evaluated by various dimensional KPIs, we prove that LSPs can gain support in their operations management, and city administration can also timely manage urban resources and assess the impacts of multiple aspects. The procedures of CDTs building and interacting with the context for decision-making can be illustrated in Figure 53.

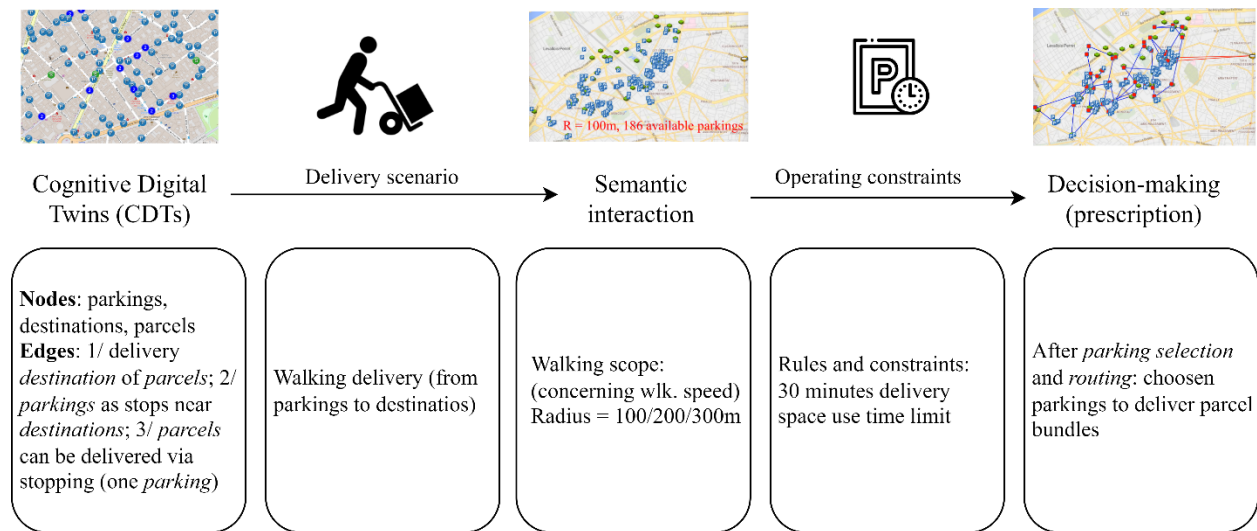


Figure 53. An example of cognitive digital twins for decision-making in operations management.

The starting points of our solution are heterogeneous stakeholders, a dynamic operating environment, the rare awareness about urban resources, and highly fragmented freight flows. After validating the effectiveness to apply semantic technologies and digital twins in logistics and supply chain management, these challenges can somehow be faced.

Semantic interoperability provides opportunities for integrating multiple stakeholders, where they can share objects and collaborate with each other. Additionally, this integration will help build an operating environment with a more comprehensive perspective. It should be noted that the involvement of city administration is crucial for sharing urban resources,

such as the importance of delivery spaces to freight parking. The dynamic state changing of objects will be real-time synchronized with their DTs and interpreted into their corresponding CDTs. Parcels can be consolidated through the design of operation strategies or coordination mechanisms, which will be reflected in the interaction of CDTs. For example, in the case study, we consider parcel consolidation in parking selection, and the semantic interaction of CDTs extend the delivery region to deliver more parcels at once.

7.2 Potential extensions of the research

We have studied the application of semantic technologies and Digital Twin to face the challenge of heterogeneity between stakeholders, inefficient urban resource utilization because of “information blindness” and lack of planning from a global view. Specifically, semantic technologies help integrate heterogeneous stakeholders’ data to describe the dynamic urban delivery environment from their view but through a set of standard conceptual vocabularies. Digital Twins are composed of the semantic description as the networked virtual replicas to mirror their physical objects and relationships.

Regarding the future directions of this research, it can be considered from the development of CDTs to perform in a self-organizing manner to achieve a multi-agent system; more applications of semantic technologies to serve the reasoning and learning of CDTs; the innovative services created based on CDTs to generate concrete benefits in city logistics operations.

7.2.1 Multi-agent system

Multi-Agent Systems (MAS) are composed of multiple intelligent, interactable, autonomous agents to collaborate to solve a complex task. These tasks are too difficult or impossible to be handled by one of the individual agents or a monolithic system. Thus, MAS is inevitably to be more advanced than monolithic systems, which depend on internally stored

data to train the machine and robots to help them find the optimal behaviors. In MAS, an *agent* is defined as an entity performed in an environment and senses various parameters that can be used to make decisions based on the objective of the entity, follow the made decisions, the entity can perform the necessary action on the environment (Dorri, Kanhere, and Jurdak 2018). Thus, from the definitions, we can see that MAS is a cooperated, holonic, dynamic, and evolvable system, which means agents equipped with intelligence that can learn from the environment they are operating, and decide their interactive and reactive behaviors based on the dynamic states of other agents and the whole environment.

The interactive and reactive behaviors of agents can show us the essence and highlights of MAS. Some recognized developing trends of MAS need to be marked. First, a specific agent needs to be clear that which information has to be informed to other agents. It requires the agents to conceal private information and does not disclose unnecessary information. Second, an individual agent can model other agents' actions or reactions, and furthermore, find the reasons behind their behaviors to support their decision-making on their own performance. Third, agents can continuously model other agents' behavior and record the significant changes, these logs can help with adjusting their further reactions to others. Lastly, each agent can simulate their potential response solutions by considering other agents' reactions and the costs and effects, on this basis, the more beneficial solution can be chosen and put into interaction.

Concerning the current research in Multi-Agent Systems, Barbosa et al. (2015) proposed an approach named ADACOR² to build a MAS to tackle complex systems facing problems. This method achieves a better overall performance via a two-dimensional self-organization mechanism, i.e., behavioral and structural. Specifically, in the behavioral aspect, when unpredictable perturbations appear, each agent can perform dynamic behavioral self-organization to contribute to minimal overall performance degradation. Besides, task handling in this system is in a structural self-organization manner, which means agents can collect information related to their set objective, calculate the outputs based on their special condition, and continuously share with other agents to find the best-performed solution. Therefore, this system is more advantageous in the quickly changing environment. In addition, van Duin et al. (2020) studied the self-organization between vehicles, parcels, and supporting

platforms to achieve a real-time intermodal last-mile parcel delivery. This method regards parcels, vehicles, and platforms as individual agents, the parcel allocation and route construction will be determined via their mutual interaction. The results show that this new method gains an 18.1% reduction in the vehicle distance traveled. And they simultaneously tested that when the number of parcels increased and the collaborative delivery was enabled among multiple operators, it can gain better operational efficiency, i.e., 24.8% less vehicle distance traveled.

Cognitive Digital Twins (CDTs) play the intelligent, self-organizing, consistently evolving, and learning agents in MAS. They synchronize the information with their physical twins consistently and collect information from other CDTs in cyberspace. Based on this collected information, various potential problem solutions can be generated and evaluated via multi-agent simulation. More importantly, each agent made decisions based on simulating other agents' reactions and the effect made on the whole system, and these outputs will help an agent to decide the next-step behavior. Some traits of CDTs in MAS need to be noted. First, the cognition of CDTs shows in the perception of the context and other agents. In our research, it has been demonstrated and validated in building the relationships between CDTs based on semantic interoperability, which will further benefit and assist the awareness of individual CDTs towards the whole context. Besides, CDTs can pay attention to objective-related tasks and other agents' dynamic states. For example, assuming that the goal of the vehicle agent is to deliver the parcels at a minimal operational cost. In the delivery, the vehicle CDT will consistently focus on the status of the relevant objects and the context. It includes the available transiting transport means, the availability of the delivery spaces around the destinations, and the accessibility of the waiting customers, etc. Apart from considering the real-time state of resources and their relations, they need to retrieve useful information to support action to achieve the objective, such as reasoning the potential failed delivery. Reasoning in CDTs aims at supporting and finding accurate problem solutions, like providing delivery alternatives to the customers of a potential failed delivery, such as parcel lockers, trunk delivery, or delivery to the neighbors. Eventually, CDTs can learn from the customer-made decisions and the actual operating performance, which means CDTs are

responsible to transfer the individual experiences of the physical twins into reusable and shareable knowledge to support future operations.

7.2.2 Knowledge Graph

Knowledge Graph (KG) is a quickly advancing application of semantic technologies, which attracts lots of interest after it was first officially proposed by Google in 2012. It structuralizes datasets in a graph-based and semantic manner, i.e., compatible with the Resource Description Framework (RDF) data model and has an ontology as their schema (J. Z. Pan et al. 2017). Current KG applications include question-answering, recommending systems, and information retrieval. The main objectives of KG are querying the existing knowledge, reasoning, and deducing the existing knowledge representations to infer new facts. And the underlying technologies and KG applications have been clearly illustrated by the state-of-the-art review of Ji et al. (2022), including knowledge representation learning, knowledge acquisition, temporal knowledge graph, and knowledge-aware applications.

From the semantic view, networked CDTs is a dynamic knowledge graphs that timely synchronized with objects' state changing. This dynamic KG enabled by DT has already been put into practice in the UK for a world avatar project (Akroyd et al. 2021), but herein we contribute to developing this dynamic KG orchestrating with DTs for smart city logistics purposes. Concerning the properties of CDTs are always changing, because logistics demands and urban resource availability are dynamic, we propose the following two potential KG applications in city logistics operations management, named track and trace and analysis of root causes and impacts.

Track and trace are to identify possible problems in operations by knowledge acquisition from the existing facts, and in the same way to match supply and demands to assign tasks. The current state-of-the-art research in this field aims at managing supply chain risks (Zhang et al. 2019; Kosasih et al. 2022) and allocating resources in production logistics (Zhao et al.

2022). Based on this research status, KG can be applied in city logistics to recognize the recognition of the potential risks and satisfy logistics demands by providing available urban resources. For example, traffic congestion can be predicted by reasoning the relationship between parcel destinations, expected delivery time windows, and the location of the vehicle. The time window can perform as the reference for the appearance of the vehicle in a particular area, and the distance between the vehicle and destination can be used for estimating the ETA of the vehicle. Besides, if dynamic knowledge about the driving vehicle can be provided, the estimation of ETA and the possibility of congestion will be more accurate. Apart from traffic anticipation, available resources can be matched regarding the needs of different transporting modes as operations support. When a vehicle is approaching the destinations, the connected available urban resources (CDTs) can be queried out to aid the specific transport mode. For example, querying parkings for deliverymen to serve walking delivery, offering autonomous vehicles as the mobile transit hub to relay the last 100 meter delivery, or querying the parcel lockers as an alternative for failed delivery if the connection between customer and destination is missing.

Analyzing the dependence of knowledge representations can help find root causes and assess impacts. As aforementioned, KG mainly contains RDF to process semantics of the DTs' state data into graph entities (semantic part of CDTs), and ontology encoding by Web Ontology Language (OWL) function for providing type information and other constraints about these entities. The analytics will perform both considering dynamic changes in CDTs and existing knowledge presented in KG. Because KG helps with extracting classes from specific instances and describes the relationships between the classes, as well as the various ranges and domains they have. It can help transfer our view from instances to classes, and also present all the potential relationships they can have with other classes. This view changing makes our concentration not on the specific events but the classes and dependent ones, which provides us a more comprehensive perspective to find the root causes and assess impacts. For example, if all these events synchronized in CDTs have converged to very few classes in KG, the root causes will be found. Additionally, if one event happens in CDT, the KG shows its relevant classes depending on many classes. It means any small change in this

CDT and its corresponding physical object can have a big impact on the relevant objects in the operations.

7.2.3 Service innovation

Service innovation is founded on resource integration and a platform is crucial to support efficient and effective service exchange (Lusch and Nambisan 2015). CSCL is based on integrating heterogeneous objects for operations management and urban sustainability, and a federative platform was provided to innovate service based on the integrated resources.

Identifying the issues and challenges related to operations and sustainability is an essential initiation for service innovation. For example, parking issue is a pain point for both LSPs and city administration. LSPs need to park frequently in daily delivery with hardly knowing the availability, and government publishes freight policies to improve urban resource use efficiency and sustainability. However, because of the heterogeneity in an objective and the lack of a platform for cooperation, it is rare and tough for these two key stakeholders to communicate for resource allocation to support operations. Starting from this problem, and concern semantic interoperability of CDTs can work for integration and networked CDTs can serve for cooperation, freight parking management service was provided to connect the two heterogeneous parties for cooperation. As a result, our work has proved that CDTs can function well to help both stakeholders in operations management and the evaluation of freight policies.

From this view, we observe that effective service innovation needs to combine the needs of multiple stakeholders translated from challenges in city logistics and the traits of CDTs. Specifically, the stakeholders' demands are various, but we focus on and discuss the main two categories herein, named asset management and operations management. Regarding the traits, CDTs mainly contains three characteristics: the bi-directional *connection* between physical objects and digital replica, semantic *interoperability* enabled by semantic technologies, and *simulating* capability for prediction and prescription. Our systematic literature review has extracted eight types of services that can be provided by CDTs. On this

basis, we will discuss how service innovation can extend the effects and impacts of CDTs, and ultimately realize Cognitive Smart City Logistics.

The first category of logistics demands is asset management, including the facilities and transport vehicles. It is crucial since logistics is an asset-intensive industry. Operators need to pay attention to the assets' lifecycle, in case there are potential risks or faults that hinder normal operations and greatly increase costs. These underlying faults can be predicted by CDTs' simulation or detected by CDTs' consistent monitoring, and they can be solved by maintenance. So innovating services can focus on disruption prediction, monitoring, and maintenance. Besides, inside the facilities, CDTs will synchronize their dynamic states and perform semantic interaction to allocate resources. Also, the allocating efficiencies will be collected as input to help the learning and evolution of CDTs. Regarding the operators working in-site, CDTs and their corresponding assets can be organized in a human-centric way to co-create value, which is the highlight of Industry 5.0 (Leng et al. 2022). Track and trace transport vehicles are the basic functions of CDTs that can be done by monitoring. Besides, CDTs of vehicles will connect with loaded goods as well as infrastructure and urban resources, and these connections are changing with the vehicle moving and the goods being delivered. Thus, services need to be created to aid in selecting the optimal resources and reporting the operating performance. Also, innovative services can analyze impacts from various aspects for the reference of the public sector.

Second, the efficiency and effectiveness of Operations Management (OM) will significantly influence operating costs and urban sustainability. City logistics operations management is using assets, workforce, and infrastructure to deliver goods and logistics services in an efficient manner to output profit, these processes have been shown on the left hand of Figure 54. OM is high-frequency and costly so it is critical for logistics service providers. Assets, workforce, and infrastructure work as the foundations and base of operations management. The assets include transport vehicles and facilities. The workforce is composed of employed or crowdsourced staff. The infrastructure contains roads, delivery spaces, curbs, etc. To deliver goods and provide services, apart from the support of resources and assets, we need concern about the way to use these resources, the relevant transport modes selection, various regulations, and so on. Eventually, the goods will be delivered with

satisfying a certain service level. The properties of goods varied, such as food, perishable products, and parcels, and overall shows the trend of smaller goods. The service mainly focuses on delivery speed and on-time delivery, such as same-day or even within fifteen minutes, and other services include the redelivery the failed ones and goods return service. Therefore, CDTs work for monitoring the dynamics of owned or shared assets, workforce, and infrastructure, i.e., representing physical space via CDTs and supporting the semantic-enabled object sharing. Based on the semantic interaction of CDTs, simulation in the cyberspace of CDTs will be conducted to make decisions, and the attributes of goods and provide services will play as the constraints of the decision-making processes. All made decisions will be used as the input for the iteration and evolution of CDTs. The involvement of CDTs in city logistics operations management is presented in Figure 54.

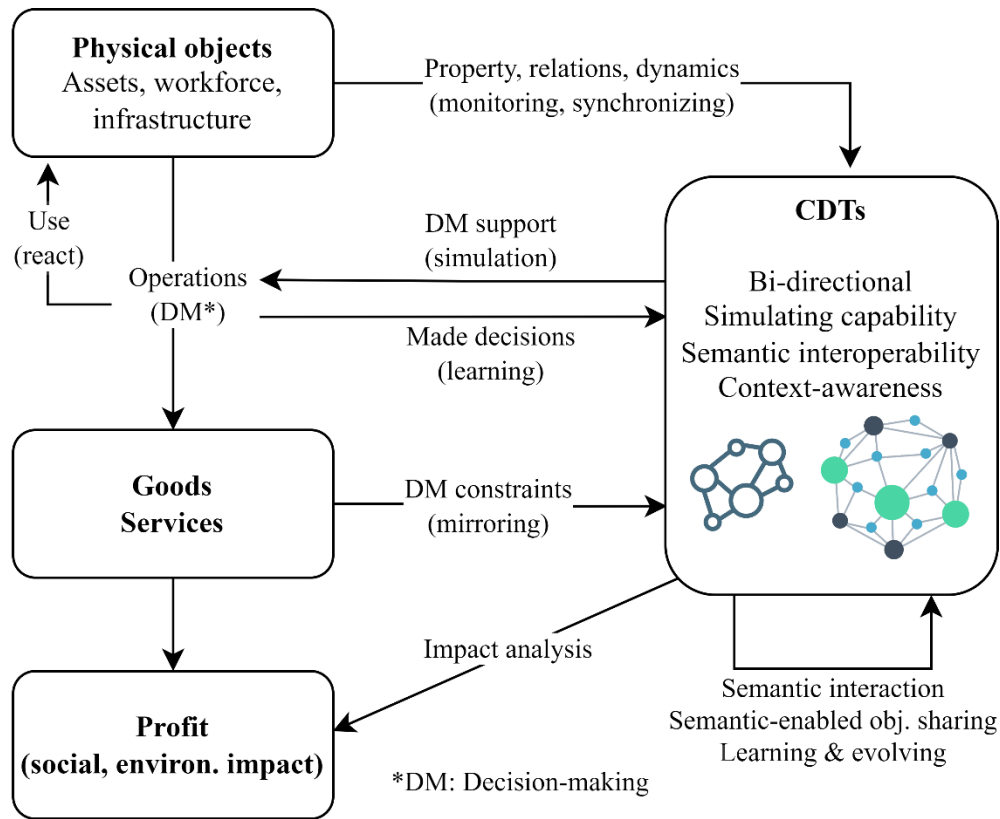


Figure 54. Service innovation in operations management orchestrating with CDTs performing and evolving.

7.3 Limits of this work

7.3.1 Limits in data source diversity

Our research considers synchronizing the object states into their corresponding digital twins and enhanced by semantics to form their Cognitive Digital Twins. We assume the delivery spaces are always available, but since their states are real-time changing, this dynamic state needs to be timely synchronized and updated. In this case, the information on available objects can be accurate when CDTs interact with the available and accessible resources. For example, the dynamic availability of delivery spaces is so important to reserve and use them, as well as the routing before arriving there. Regarding the routing problem, the consideration of real-time traffic information can estimate the arrival time more accurately, and further better support the prediction of using time slots and the delivery spaces reservation.

Regarding the Open Data shared by the public sector, we only consider the location information of the delivery spaces. In fact, there are more properties of delivery spaces that can be considered, including area surface, accessible path types and actual occupancy. All this more detailed information can be used to support more precise reasoning and decision-making. In addition, more data sources from various stakeholders in city logistics can be considered to evaluate the value of the work and the related impacts.

7.3.2 Limits in case study and formulation

The current case study only involves two main stakeholders in city logistics, Logistics Service Providers (LSPs) and the city administration, as shown in Figure 21. And the scale of the use case is small, regarding the number of orders, delivery vehicles, and the regulations considered. For future research, it is worthwhile to extend the applied scenarios of the architectural framework to study the collaboration between LSPs, and the involvement of customers and their dynamic delivery requirements. More precisely, customers can provide

their expected delivery time window or choose delivery alternatives to support the operations, and the accurate information from the end-users can also ensure the service-providing at a certain service level. Likewise, crowdsourcing workers, act as the dynamic workforce supply that can play an important role in multi-modal delivery to support efficient delivery fulfillment. With more stakeholder participation, it can facilitate the building of a more comprehensive city logistics operating environment. Based on this full-fledge context, more rich logistics scenarios can be designed, and operators and other stakeholders can create more innovative logistics services to support operations and performance evaluation. In addition, more advanced technologies in city logistics can be concerned with scenario design, such as autonomous vehicles and robots, drones, and so on.

The current proposed model, i.e., the parking selection and routing models, both consider the ideal situation. For example, in the optimization-based simulation, there is only one vehicle, and its capacity was not considered. It is essentially a Travelling Salesman Problem (TSP), but the vehicle stopping time is varied, which depends on the number of parcels delivered via each parking. In addition, the routing problem is assumed that there is no congestion and that all the delivery spaces are available. However, the contribution of our research is to validate the four-layer architectural framework can work well in integrating multiple heterogenous data sources via semantic technologies to describe the operating environment and generate substantial operating benefits. Thus, as aforementioned in limits of data needs to be broken. In this context, multiple data sources can be converged, and the real-time traffic information, delivery space availability, and object states of other resources can be more precise and accurate. On this basis, the information to support operating decision-making can be richer, and more advanced algorithms can be used to support operations planning and real-time decision-making.

7.3.3 Limits in reasoning

In our research we use reasoning to search the available resources, i.e., querying the available objects based on the set rules. Thus, reasoning plays an information retrieval role here. But its capable functions can be exploited further, such as inferring the nonexistent

knowledge based on the logical relationships between objects. So departing from this powerful function, the graph-based algorithm can be used to deduce the potential but not described relationships between objects.

7.3.4 Limits in technology analysis for implementation

This work validates the heterogeneous stakeholders' data can be integrated to assist real-time decision-making in city logistics operations. However, we still need to further investigate the impact of all the used technologies on the individual stakeholders, including their concerns, their willingness to participate, the concrete benefits they would like to gain from this sharing and coordination. Based on these surveys, we can discuss the efficient and effective business models to properly share the gains and also pains and to encourage and stimulate stakeholders' participation and continuous contribution. In addition, in order to move forward to put this work into practice, we need to refine the practicing procedures, like negotiation protocols to integrate stakeholders and their owned decision systems, and also evaluate implementation costs of the work, including the and expense of the development of the infrastructure and the development of software systems.

7.4 Publications

Journal:

- I. Liu, Y., Pan, S., Ballot, E. (2023). The State of the art of Digital Twins in logistics operations: applications, services, maturity, and opportunities. (Reviewing for submission)
- II. Liu, Y., Pan, S., Ballot, E. (2023). Cognitive Digital Twins for Smart City Logistics: architecture, framework, and application. (Preparing for submission)

Conference:

- I. Liu, Y., Folz, P., Pan, S., Ramparany, F., Bolle, S., Ballot, E., & Coupaye, T. (2021, September). Digital Twin-Driven Approach for Smart City Logistics: The Case of Freight Parking Management. In *IFIP International Conference on Advances in Production Management Systems* (pp. 237-246). Springer, Cham.
- II. Liu, Y., Pan, S., Ballot, E. (2021) Physical Internet in city logistics: Digital-Twin-driven modeling and implementation, International Physical Internet Conference 2021
- III. Liu, Y., Pan, S., Ballot, E. (2022) Connected Freight Parking in Smart City Logistics, Transport Research Arena Conference Lisbon 2022

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APPENDIX

Parking selected	Driving distance (km)	Walking distance (km)	Emission (g)	Delivery time (min)	To-door time (min)	To-parking time (min)	Delivery cost (€)	To-door cost (€)	To-parking cost (€)
54	48.1	4.9	7602	339	195	144	254	140	114

Table A.1. Simulation results of delivery via the closest parking (S1).

Catchment radius (m)	Parking pool	Parking selected	Driving distance (km)	Walking distance (km)	Emission (g)	Delivery time (min)	To-door time (min)	To-parking time (min)	Delivery cost (€)	To-door cost (€)	To-parking cost (€)
100	182	38	42.6	7.1	6723	344	217	127	256	155	101
150	320	28	37.3	9.1	5899	348	236	112	258	169	89
200	466	24	35.7	11	5645	374	267	107	276	191	85
250	566	23	35	13.1	5535	397	292	105	292	209	83
300	647	18	31.4	15.4	4965	415	321	94	305	230	75

Table A.2. Simulation results of parcel consolidation with driver delivery (S2).

Catchment radius (m)	Parking selected	Number of trans-shipment stops	Number of parcel delivery via modal shift	Driving distance (km)	Walking distance (km)	Cycling distance (km)	Emission (g)	Delivery time (min)	To-door time (min)	To-parking time (min)	To-door cost (€)	To-parking cost (€)
100	38	2	17	42	5.1	2	6641	309	189	126	135	100
150	28	5	63	37.1	3.8	5.2	5864	246	151	111	108	88
200	24	8	92	35.8	2.6	8.8	5663	213	134	107	95	85
250	20	9	110	34.7	1.4	12.4	5476	180	123	103	86	82
300	12	11	141	26.5	0.2	19.5	4185	118	123	79	84	63

Table A.3. Simulation results of parcel consolidation with E-cargo bike-based modal shift (S3).

RÉSUMÉ

La logistique urbaine, également appelée ici livraison du dernier kilomètre, vise à transporter de manière efficace et efficiente les marchandises depuis le centre de distribution jusqu'à la destination finale afin de satisfaire les demandes des consommateurs dans les zones urbaines. Son importance est notable puisqu'elle joue le rôle de dernier maillon de la chaîne d'approvisionnement et représente plus de 20 % du coût global. Il a joué un rôle important dans l'approvisionnement en marchandises et en nourriture lors de l'épidémie de COVID-19, en particulier pendant le confinement. Elle est donc devenue de plus en plus essentielle aux yeux du gouvernement et du public. De plus, son importance se manifeste par des externalités négatives pour la durabilité urbaine, telles que la congestion du trafic, la sécurité routière, le bruit et la pollution de l'air. C'est pourquoi de nombreuses villes, en particulier les mégapoles à forte densité de population, ont imposé des réglementations plus strictes en matière de fret urbain afin de rendre les villes plus durables et plus vivables. La mise en œuvre de ces politiques n'est pas l'affaire d'une seule partie. Elles ont besoin de l'engagement d'autres parties prenantes et d'obtenir un retour d'information sur leurs changements de comportement pour évaluer l'efficacité de la politique. Les prestataires de services logistiques (PSL), l'une des principales parties prenantes, doivent opérer dans un environnement de plus en plus difficile et complexe tout en respectant les politiques. La complexité de la gestion de leurs opérations provient de la forte segmentation des flux de marchandises et de la disponibilité dynamique des ressources urbaines soutenues par la logistique. Par conséquent, ils doivent acquérir les états changeants des ressources urbaines pour soutenir la planification de leurs opérations dans un tel environnement dynamique.

Dans le contexte de recherche ci-dessus, cette thèse étudie une solution numérique dans le contexte des villes intelligentes, où les objets et les données sont connectés via les technologies IoT/ICT. Plus précisément, nous étudions les jumeaux numériques cognitifs, les jumeaux numériques (DT) avec des capacités sémantiques accrues. Et comment ils peuvent améliorer la connaissance en temps réel des demandes et des ressources logistiques à l'échelle de la ville pour optimiser la planification des opérations et l'allocation des ressources. Un cadre d'architecture à quatre couches est développé pour intégrer les objets et systèmes logistiques individuels dans les villes intelligentes à un niveau sémantique. Les technologies et normes sous-jacentes sont, par exemple, Property Graph, Web Ontology Language (OWL), Knowledge Graph et Web of Things (WoT). Ensuite, une étude de cas d'utilisation de la livraison de colis à Paris est menée sur une plateforme DT réelle appelée Thing in the future (Thing'in), couplée à une simulation à base d'agents sur AnyLogic pour démontrer une application réelle de notre approche. Les résultats impliquent que lorsque la DT individuelle, détenue par un acteur de la logistique urbaine, est capable de communiquer avec l'environnement dynamique, elle peut améliorer l'efficacité de la logistique tout en facilitant l'évaluation des politiques. Il en résultera moins d'externalités négatives, une meilleure utilisation des ressources et une meilleure compréhension des municipalités pour améliorer l'élaboration des politiques. Notre travail met également en évidence le potentiel de l'offre de nouveaux services commerciaux aux prestataires de services logistiques. Sur la base de nos travaux, un prototype d'application réelle est développé par notre partenaire pour faciliter la livraison en voiture et à pied, ce qui montre l'applicabilité concrète de nos travaux.

MOTS CLÉS

Logistique urbaine, jumeaux numériques cognitifs, graphe de connaissances, ontologie et sémantique, villes intelligentes, durabilité, Web des objets.

ABSTRACT

City logistics, also named last-mile delivery herein, aims to efficiently and effectively transport goods from the distribution hub to the final destination efficiently and effectively to satisfy consumer demands in urban areas. Its significance is notable since it plays as the last leg of the supply chain and accounts for more than 20% of the overall cost. It was prominent to supply goods and food during the COVID-19 outbreak, especially during the lockdown. Thus, it has become increasingly essential in the eyes of the government and the public. Also, its importance is manifested in negative externalities toward urban sustainability, such as traffic congestion, road safety, noise, and air pollution. Hence, many cities, especially mega-cities with dense populations, have imposed stricter urban freight regulations to make cities more sustainable and livable. It is not a matter for one party to implement the policies. They need other stakeholders' engagement and further obtain feedback from their behavior changes to evaluate the policy's effectiveness. Logistics Service Provider (LSP), one key stakeholder, must operate in an increasingly difficult and complex environment while meeting the policies. The complexity of their operations management comes from the highly segmented freight flows and dynamic availability of logistics-supported urban resources. Therefore, they need to gain the time-changing states of urban resources to support their operations planning in such a dynamic environment.

Under the above research background, this thesis studies a digital solution in the Smart Cities context, where the objects and data are connected via IoT/ICT technologies. More specifically, we investigate Cognitive Digital Twins, Digital Twins (DT) with augmented semantic capabilities. And how they can enhance the real-time knowledge of city-wide logistics demands and resources to optimize operations planning and resource allocation. A four-layer architecture framework is developed to integrate individual logistics objects and systems into Smart Cities at a semantic level. The underlying enabling technologies and standards are, for example, Property Graph, Web Ontology Language (OWL), Knowledge Graph, and Web of Things (WoT). Then, a use case study of parcel delivery in Paris is conducted upon a real-life DT platform called Thing in the future (Thing'in), coupled with an agent-based simulation on AnyLogic to demonstrate a real-world application of our approach. The results imply that when individual DT, owned by one stakeholder of city logistics, is capable of communicating with the dynamic environment, it can improve logistics efficiency while facilitating policy evaluation. It will result in fewer negative externalities, better utilization of resources, and provide insights for city municipalities to improve policy-making. Our work also showcases the potential of offering new business services to logistics service providers. Based on our work, an actual app prototype is developed by our partner to aid driving and walking delivery, showing our work's concrete applicability.

KEYWORDS

City Logistics, Cognitive Digital Twins, Knowledge Graph, Ontology and Semantics, Smart Cities, Sustainability, Web of Things