Digital Twin-Driven Approach for Smart City Logistics: The Case of Freight Parking Management

Yu Liu[1(✉)], Pauline Folz[2], Shenle Pan[1], Fano Ramparany[2], Sébastien Bolle[2], Eric Ballot[1], and Thierry Coupaye[2]

[1] Centre de Gestion Scientifique - I3 - UMR CNRS 9217, MINES ParisTech, PSL Research University, 60 boulevard Saint-Michel, 75006 Paris, France
{yu.liu,shenle.pan,eric.ballot}@mines-paristech.fr
[2] Orange Labs, Paris, France
{pauline.folz,fano.ramparany,sebastien.bolle,thierry.coupaye}@orange.com

Abstract. According to the United Nations' prediction, the world is expected to have 43 megacities that host more than 10 million inhabitants by 2030. City logistics for freight distribution is a challenging and crucial problem for these cities. Recent disruptive approaches such as *Smart City* provide us a new perspective to investigate the problem as well as for decision making. It creates a pervasive and mobile computing environment that allows the city itself to be overlaid with sensing and actuation, embedded with "smart things" to develop an "ambient intelligence." By choosing this angle, this work investigates the problem of freight parking management for last-mile delivery in smart city, called *Smart City Logistics Parking (SCLP)*. A use case is conceptualized and modeled via a bottom-up approach. The bottom-layer aims to represent the structure of the SCLP, i.e., the physical elements constituting the SCLP physical infrastructure into a digital representation, a.k.a a Digital Twin of the SCLP. Property Graph modeling is applied at this step as a meta-model to formulate the object relationships with properties. The upper-layer makes use of associated ontologies to add semantics to the structural description of the SCLP. The built model is then implemented into a Digital Twin experimental platform, namely *Thing in the Future (Thing'in in short)* from *Orange Labs*. The modeling work presented in this paper encourages future works on simulation of the decision-making processes based on the Digital Twin platform.

Keywords: City Logistics · Smart City · Digital Twin · Sustainability · Freight parking management · Last-Mile Delivery · Property Graph · Ontology · Semantics

1 Introduction

City logistics is concerned with freight distribution in the urban area, aimed at sustainability and livability while managing the inbound, outbound, and inner urban freight. Its

© IFIP International Federation for Information Processing 2021
Published by Springer Nature Switzerland AG 2021
A. Dolgui et al. (Eds.): APMS 2021, IFIP AICT 633, pp. 237–246, 2021.
https://doi.org/10.1007/978-3-030-85910-7_25

performance not only results in operational cost but in other external factors, like noise pollution, air pollution, congestion, accidents, etc. [1]. Research shows that depending on the pollutant considered, commercial vehicles (for goods movement) are responsible for 20–30% of total vehicle kilometers, and for 16%–50% of air pollutants generated by all transport activities in cities [2]. Hence, for a sustainable and livable city, many city logistics solutions are provided, such as adopting green vehicles to reduce emissions, using urban consolidation centers for the higher loading rate of vehicles, and optimizing delivery routes to reduce transport cost and congestion. However, the efficiency and effectiveness of these solutions rely more and more on the technologies that provide (real-time) information assisting in the decision-making processes, such as Information and Communication Technologies (ICT) and Internet of Things (IoT), data analytics, and visualization.

In this context, the paradigm of *Smart City* (or *Smart Cities*) provides a new research angle to the problem of city logistics [3]. Generally speaking, smart city "is a place where traditional networks and services are made more efficient with digital and telecommunication technologies for the benefit of its inhabitants and business" [4]. To this end, IoT and ICT technologies are applied to converge the physical infrastructure (or means) and digital computational environment. An emerging associated concept, explored in this work, is the *Digital Twin.* Digital Twin was a concept come from the practice when NASA created a duplicated physical system at ground level to twinning the systems in space in 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* [5]. 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* in [6]. With this trend, there are some applications in logistics and supply chain management, for instance, supply chain network mapping and visulizing for disruptive risk management [7], production logistics synchronization with digital twin system for the real-time monitor, decision and control [8].

Choosing the angle of Smart City, this paper investigates the concept of S*mart city logistics* via studying an important practical issue that is the *freight parking management* in last-mile delivery [9]. This work considers Smart city logistics as a self-cognitive and self-organized system to transport freight in an urban area, with mobility, safety, and sustainability. As part of such a system, freight parking management focuses on parking space utilization and efficiency. Smart parking was well studied for passenger vehicles, like WSN (Wireless Sensor Networks)-Based System for Parking Garages environment monitor and management [10], smartphone's sensors for detecting parking events and providing real-time parking availability [11]. However, recent studies also show that the parking problem is equally critical for commercial vehicles for freight distribution (e.g., heavy or light-duty vehicles, motors). For example, cruising for parking takes 28% of the trip time for commercial vehicles in Seattle downtown, and around 1.1h per commercial vehicle tour [12]. The Smart logistics parking is therefore put forward to emphasize the efficiency of logistics distribution and last-mile delivery, by highlighting the need for infrastructure and various information demands related to freight parking management.

Following this, we study a case called *Smart City Logistics Parking* (SCLP), through conceptualization, modeling, and implementation. The research intends to discover the essential information that is needed from urban infrastructure for freight parking management. It can be considered among the first contributions that propose to use Digital Twins of the urban facilities, where the multi-source data are well organized in multilevel scale, from single objects to complex systems structure and semantics.

Our research questions are as follows: first, what kind of data and objects are (the sources of data) needed to solve the SCLP problem? Second, how to model the data and shape the objects in the digital world? Third, how to implement this model to display the interconnection of the data sources and the physical entities?

The paper is structured as follows. Section 2 clarifies the research methodology used in this research, Sect. 3 conceptualizes the SCLP in the context of smart logistics distribution schemes, Sect. 4 presents the bottom-up modeling approach for the SCLP scenario, Sect. 5 delivers the implementation and visualization of the model in *Thing'in*, and Sect. 6 summarizes the novel discoveries of the present work and points out the perspectives for future work.

2 Methodology

To investigate the SCLP problem, the work applies the conceptual modeling for the simulation approach [13]. A simplified real-life scenario of last-mile delivery is first conceptualized in which the freight parking management should be addressed with the support of interconnected data and objects. Next, this scenario is modeled with a bottom-up approach that includes all the scenario-related objects and depicts their relationship accurately (i.e., the contents in the simulation), see Fig. 2. At the bottom layer, Property Graph modeling is applied to model the relationships of objects with properties, i.e., to describe the structure of the physical logistic system considered. In the upper layer, the semantics of objects and relationships is added by associating ontologies to them. Finally, we inject the constructed model into a digital twin-based platform, *Thing in the Future* (*Thing'in* in short), for establishing these interconnections between objects and data for decision making. Additionally, the necessary information can be queried from the platform for decision-making and simulation. Apart from the simulation section, all the modeling procedures will be described step by step and in detail in this paper.

3 Conceptualization of Smart City Logistics Parking

The last-mile delivery problem is generally defined as shipping cargo from origin A to destination B within the city. Being part of it, the Smart City Logistics Parking (SCLP) problem is concerned with finding the best parking place for last-mile delivery. This problem is a good junction of parking, final destination delivery, and transportation from infrastructure, as shown in Fig. 1.

We first identify the key elements of effective planning in last-mile delivery, including multiple transportation means, destination alternatives, real-time transit points, parking place selection, and dynamic route planning. Second, we determine the four categories of data sources and the related objects or concepts as follows: 1) vehicles that include

the information of logistics vehicles and cargo, 2) transportation network such as roads, paths, and highways, 3) stops to pause for logistics activities like transit or delivery, which especially refer to parking places in this use case, and 4) destinations where the end-customer is located. The sources will provide the real-time condition of the infrastructure, namely dynamic traffic, destination information, and the occupancy of logistics facilities. Besides, digital twins act as the counterparts of their physical objects can conserve required information of real-time status. In this way, the digital twin of all the relevant objects will be interconnected to explore the potential of an open logistics network.

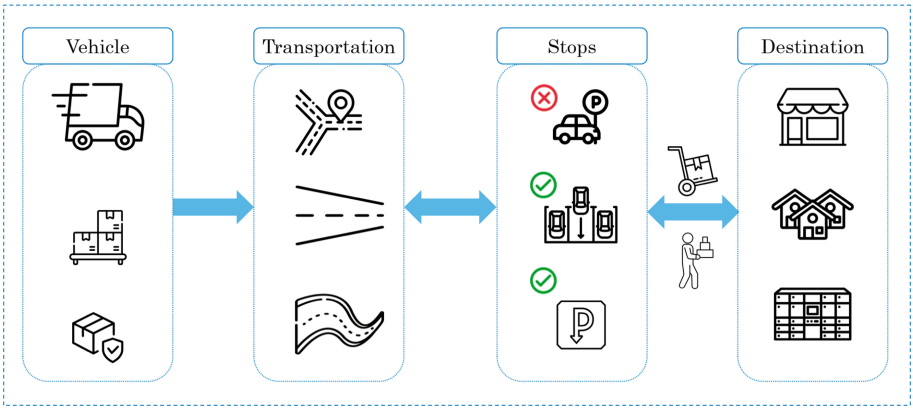

Fig. 1. Illustration of smart logistics parking in last-mile delivery.

4 Modeling

4.1 Bottom-Up Modeling Approach

Due to the complexity of the problem, a bottom-up modeling approach is adopted in this work. We start modeling based on the four types of data sources above. There are two major difficulties at this stage. On the one hand, the number of objects in each data source category is high; on the other hand, there are multiple and complex relationships among objects and among their categories. Considering these two aspects, we start modeling one data source (i.e., an object) and then integrating it upward to identify and define the data source categories. The overall modeling approach is shown in Fig. 2.

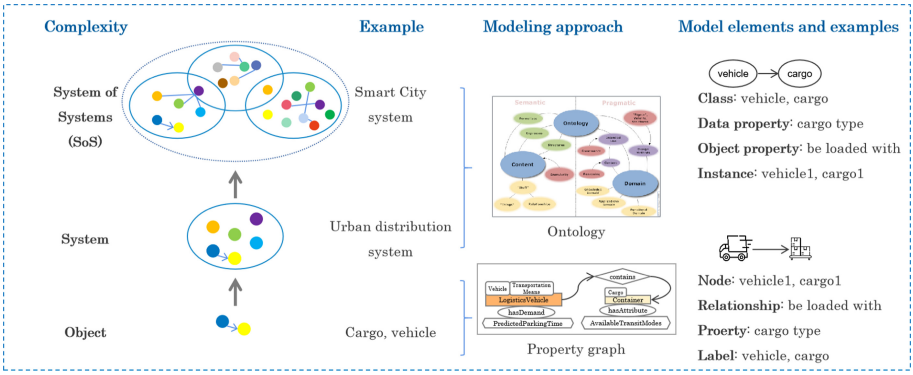

Fig. 2. The illustration of bottom-up modeling approach.

4.2 Bottom-Layer Modeling – Property Graph (PG)

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" (Fig. 3). 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.

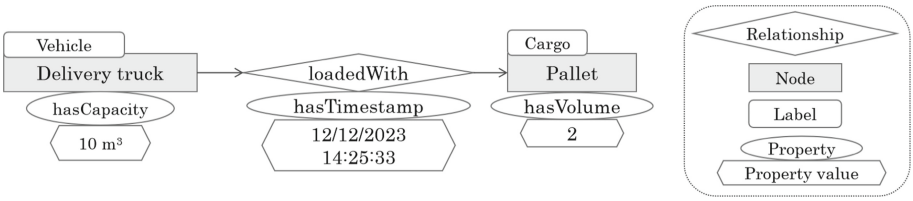

Fig. 3. The sensed information of parking state organized by Property Graph.

By combining the multiple data sources using the Property Graph formalism (Fig. 3), we can then model each object whatever its category. For instance, cargo and logistics delivery trucks in the "vehicle" category and shops in the "destination" category (Fig. 4).

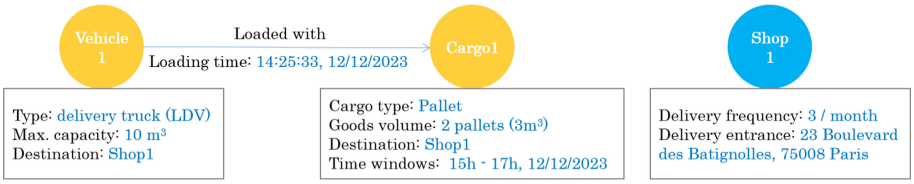

Fig. 4. Property Graph organizes data sources from different categories with their relationships.

4.3 Up-Layer Modeling – Ontology

An ontology is a shared vocabulary to represent and define a domain area. It defines concepts and relationships between those concepts [14]. We used the W3C Web Ontology Recommendation (OWL) [15] and the tool Protégé [16] 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 modeling proceeds following these steps (Fig. 5): (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 [17], Schema [18], and Mobivoc [19]. The upper ontology, such as Industrial Ontologies Foundry (IOF) [20], 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 6 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.

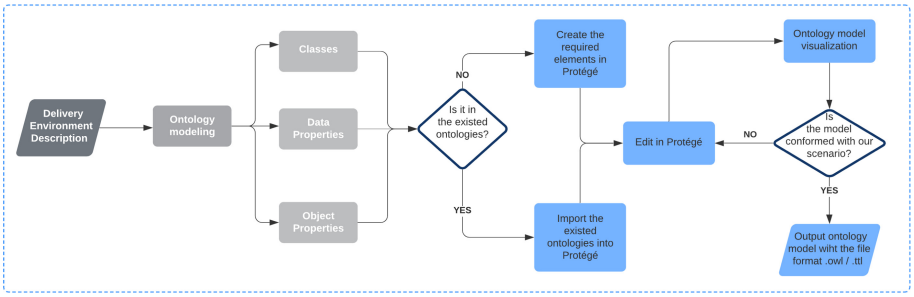

Fig. 5. Working processes in ontology modeling.

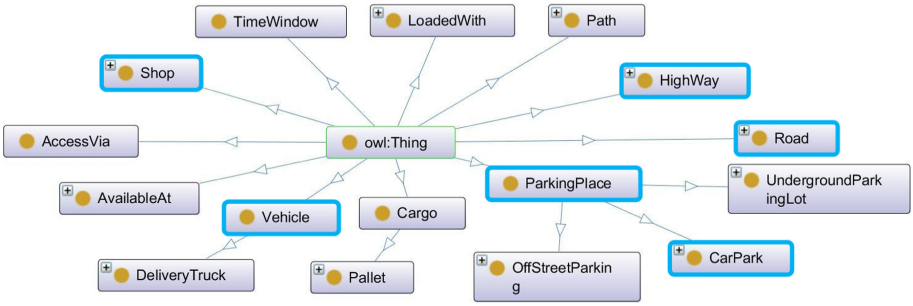

Fig. 6. Relation between classes (classes in the blue frame are from other ontologies).

5 Implementation

5.1 *Thing in the Future (Thing'in)* Platform

Thing'in is an experimental Digital Twin platform. It provides a 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 and 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.

5.2 Model Injection of a Simple Use Case

First, the ontology defined in the previous section was injected into Thing'in. Next, we defined a model for a simple use case named Smart City Logistics Parking. Then Protégé was used to create the instances of the model, where the instances represent objects of the domain of interest. The full model is displayed in Fig. 7, where purple diamonds are instances and yellow circle is the classes defined in the ontology. Finally, those instances were injected into Thing'in to create digital twins of physical objects and facilities. In Fig. 8, 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).

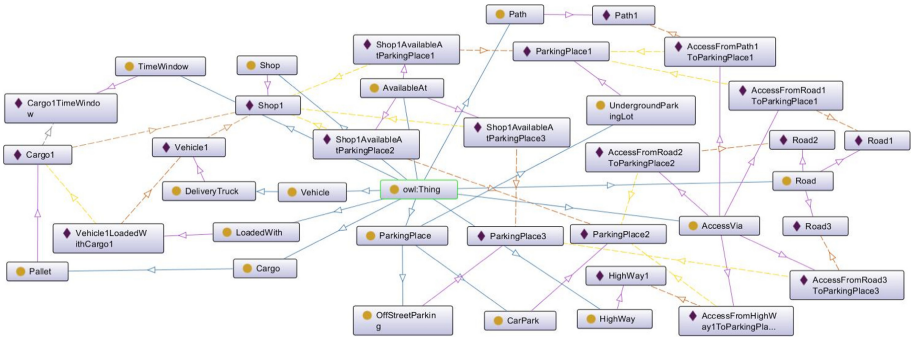

Fig. 7. Ontology model injected in Thing'in depicting the physical world of the use case.

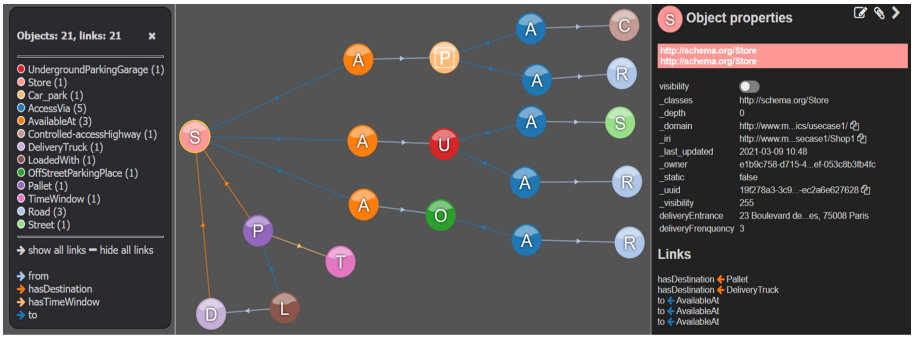

Fig. 8. Avatars created in *Thing'in* corresponding to the ontology model injected.

5.3 Reasoning in the Use Case

In this case, the vehicle loaded with the cargo queries to Thing'in platform for a suitable parking place. It will recieve 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 infrastrcutre are needed, the response will provide the specific surface area for the delivery man to check the accessibility. However, the material handling constraints will be weaken for light parcel delivery. An example of the process expressed with Thing'in query language is demonstrated in Fig. 9.

Query: My vehicle loaded with a furniture in a size of 70" * 50" * 20" and have to be delivered to shop 1, could you please recommand me with a parking place within at most 10m from Shop 1?

Thing'in query: For cargo larger than 1 pallet (l * w * h, max (l, w) > 48 ", h > 60")

```
{
 "query": [
   {
    "$domain": "http://www.minesparistech.logistics/usecase1/",
    "$classes": {
     "$any_in" : [
       "http://www.minesparistech.logistics#OffStreetParkingPlace",
       "http://schema.mobivoc.org/UndergroundParkingGarage",
       "http://www.disit.org/km4city/schema#Car_park"
      ]
    },
    "http://www.minesparistech.logistics#withCargoHandlingSpace":{
     "$gt": 0.1
    },
    "http://www.opengis.net/gml/pos": {
        "$nearSphere": {
           "$geometry": {"type": "Point", "coordinates": [2.349828, 48.83986]},
            "$maxDistance": 10
        }
    }
}
 ],
 "view": {}
}
```

For cargo in pallet (48" * 40" * x, x < 60")

```
{
 "query": [
   {
    "$domain": "http://www.minesparistech.logistics/usecase1/",
    "$classes": {
     "$any_in" : [
       "http://www.minesparistech.logistics#OffStreetParkingPlace",
       "http://schema.mobivoc.org/UndergroundParkingGarage",
       "http://www.disit.org/km4city/schema#Car_park"
      ]
    },
   "http://www.minesparistech.logistics#withLoadingBay": true,
   "http://www.opengis.net/gml/pos": {
       "$nearSphere": {
          "$geometry": {"type": "Point", "coordinates": [2.349828, 48.839863]},
           "$maxDistance": 10
       }
    }
  }
 ],
 "view": {}
}
```

Fig. 9. Demonstration of the query of a parking space based on cargo type.

6 Conclusion and Future Work

This paper presents the first step of the ongoing research work that focuses on modeling the smart city logistics scenario, and more specifically, the freight parking management problem called Smart City Logistics Parking. We first conceptualized a use case in last-mile delivery, then modeled it via a bottom-up approach. In the bottom-layer, property graph helps organize the key information into a Digital Twin, which represents in the digital world its physical counterpart. In the up-layer, the use case's ontology shows validity in defining concepts to clarify the semantic environment of the scenario. Then, the built model was injected into the digital-twin-based platform Thing'in. Founded on the model and the platform, the next step is to assess the value of the connected data and objects by investigating supportive information from the platform for decision-making. Simulation work can be done here to investigate decision quality and decision accuracy according to different levels of data connectivity.

Acknowledgements. This work is supported by the Physical Internet Chair at Mines ParisTech - PSL University, and the project ASAP (Awaken Sleeping Assets Project) which has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 875022.

References

1. Schroten, A., et al.: Handbook on the external costs of transport: version 2019. In: European Commission (2019)
2. Dablanc, L.: Goods transport in large European cities: difficult to organize, difficult to modernize. Transp. Res. Part A Policy Pract. **41**, 280–285 (2007)
3. Pan, S., Zhou, W., Piramuthu, S., Giannikas, V., Chen, C.: Smart city for sustainable urban freight logistics. Int. J. Prod. Res. **59**, 2079–2089 (2021)

4. European Commission. Smart cities (2019). https://ec.europa.eu/info/eu-regional-and-urban-development/topics/cities-and-urban-development/city-initiatives/smart-cities_en
5. Shafto, M., et al.: DRAFT modeling, simulation, information technology & processing roadmap - technology area 11. Natl. Aeronaut. Sp. Adm. **27** (2010)
6. The Definition of a Digital Twin | Digital Twin Consortium®. https://www.digitaltwinconsortium.org/initiatives/the-definition-of-a-digital-twin.htm
7. Ivanov, D., Dolgui, A.: A digital supply chain twin for managing the disruption risks and resilience in the era of Industry 4.0. Prod. Plan. Control **32**, 775–788 (2021)
8. Pan, Y.H., Qu, T., Wu, N.Q., Khalgui, M., Huang, G.Q.: Digital twin based real-time production logistics synchronization system in a multi-level computing architecture. J. Manuf. Syst. **58**, 246–260 (2021)
9. Jaller, M., Holguín-Veras, J., Hodge, S.: Parking in the city - challenges for Freight traffic. Transp. Res. Rec. 46–56 (2013). https://doi.org/10.3141/2379-06
10. Lin, Y.C., Cheung, W.F.: Developing WSN/BIM-based environmental monitoring management system for parking garages in smart cities. J. Manag. Eng. **36**, 1–17 (2020)
11. Krieg, J.G., Jakllari, G., Toma, H., Beylot, A.L.: Unlocking the smartphone's sensors for smart city parking. Pervasive Mob. Comput. **43**, 78–95 (2018)
12. Dalla Chiara, G., Goodchild, A.: Do commercial vehicles cruise for parking? Empir. Eviden. Seattle. Transp. Policy **97**, 26–36 (2020)
13. Liu, C., Lu, M., Johnson, S.: Simulation and optimization of temporary road network in mass earthmoving projects. In: Proceedings of the 2013 Winter Simuliation Conference - Simuliation Maketing Decision a Complex World, WSC 2013 3181–3190 (2013). https://doi.org/10.1109/WSC.2013.6721684
14. Ontologies - W3C. https://www.w3.org/standards/semanticweb/ontology
15. OWL Web Ontology Language Overview. https://www.w3.org/TR/owl-features/
16. protégé. https://protege.stanford.edu/
17. km4city, the DISIT Knowledge Model for City and Mobility. http://wlode.disit.org/WLODE/extract?url=http://www.disit.org/km4city/schema
18. Schema.org - Schema.org. https://schema.org/
19. Open Mobility Vocabulary — MobiVoc. https://www.mobivoc.org/
20. Supply Chain WG – IOF Website. https://www.industrialontologies.org/supply-chain-wg/