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Vrijhoef, R.

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Modelling and Visualizing Urban Construction Logistics and Environmental Effects with Digital Twins

Ruben Vrijhoef, r.vrijhoef@tudelft.nl
Delft University of Technology, Netherlands

Abstract
In urban settings, where cities want to pursue ambitions of clean air and zero emission transport, the construction industry with its heavy freight encounters greater difficulties and challenges than other sectors to meet the increasingly stringent emission reductions and building codes. Various construction innovations have been deemed to improve construction logistics. Solutions are offered to increase logistics efficiency, reduce construction transport movements, and related emissions.

Governments are aiming their policy instruments at incentivizing and enforcing these reductions and addressing the mitigation of other urban effects, such as reducing road damage, safety issues, disruptions and congestion. Governments and firms want to assess and demonstrate the effects of new policies and logistics measures taken in advance. Digital Twins (DT) can play a role here. However previous DT applications have often been representing building as objects statically, and not necessarily representing building as a process dynamically, including logistics, transport movements and the environmental effects including emissions.

The goal of this paper is to present a research through design approach to develop and test a DT application for modelling construction logistics, and visualizing the environmental effects. By doing so, the approach has intended to explore and demonstrate the use of DT to show the feasibility of logistics innovations. The research reported has assessed the application possibilities of DT to model and interpret construction processes and logistics, and visualizing dynamic parameters including transport movements and environmental effects. The application has been illustrated through a practical case in the city of Utrecht in the Netherlands.

Keywords
urban construction, logistics modelling, environmental effects.

1 Introduction

Logistics has been a key aspect of construction, playing a pivotal role in the success of projects. It includes the processes that ensure the availability of necessary resources on time for construction activities. This includes tasks such as project planning, delivery of resources to the construction site, managing these resources on site, and handling the flow of waste from the site (Sundquist et al. 2018). Construction projects typically involve a myriad of subcontractors, suppliers, and other stakeholders. Thus, the resources for construction projects are sourced by and from different players, from different locations, and are scheduled for different times, making the flow of logistics to and from construction sites almost continuously . Moreover, a significant portion of construction projects are concentrated in major urban areas (Vrijhoef 2020). The extensive logistics associated with these projects can significantly impact city traffic, leading to congestion that affects the cities' livability and accessibility while also increasing emissions due to the resulting traffic jams. Given these critical impacts, it is not a surprise that construction logistics attracts particular attention (Belfadel et al 2023).

1.1 Towards Smart and Sustainable Logistics

Numerous studies have demonstrated the advantages of logistics innovations in construction, such as the implementation of integrated chain management and the utilization of consolidation centers (Guisson et al 2023). These strategies have been shown to significantly reduce the volume of transportation movements to sites, which in turn leads to decreased emissions (De Bes et al 2018). Despite the promising outcomes presented by these studies, the widespread adoption of these sustainable solutions and interventions within the industry remains limited. The barriers take the form of both organizational and technical challenges. Organizational barriers encompass, among other aspects, the way how construction projects are still tendered, the lack of coordination agreements established between various parties involved, and the prevailing project-specific mindset that dominates the construction industry (Vrijhoef 2020).

These factors often leave construction stakeholders with little capacity to focus beyond ensuring the timely availability of necessary resources for their projects. Compounding the issue are the technical challenges associated with logistics. The involvement of numerous parties in a logistics chain and the persistence of conventional working methods among these parties often lead to a lack of transparency in the logistics chain. This also leads to inadequate data management practices, which further aggravates coordination issues among various logistics participants, also hindering the opportunity to derive insights and learn from data throughout these processes (Martínez-Rojas et al 2016).

While some projects may incorporate smart logistics practices during the tendering or planning phases, the monitoring of these activities during execution is frequently non-existent. This is not to say that individual parties within the logistics chain are underperforming; many might indeed be fine-tuning their operations to peak efficiency. Yet, this individual optimization does not necessarily translate to overall logistics chain efficiency. Various studies on sustainable logistics advocate for a move towards more cohesive chain management approaches, emphasizing the critical role of data management and utilization (Guerlain et al 2019). Such strategies aim to diminish the frequency of transport movements and, consequently, emissions. Examples of such practices include employing consolidations centers, material kits, and implementing integrated planning systems, all designed to streamline logistics and reduce the environmental footprint of construction activities (De Bes et al 2018).

2 Literature Review: Digital Twin Conceptual Framework

Efficient use of data and enhanced data sharing between the various involved stakeholders are seen as critical for sustainable logistics. An enabler in this regard is the concept of Digital Twins (DT). In broad terms, a DT is a dynamic virtual representation of a physical asset or process, in which the physical and virtual counterparts interact with each other to optimize the performance or the operations of the asset or process (Boje et al 2020). Through the use of technologies like the Internet of Things, big data analytics, artificial intelligence, DTs hold the promise of delivering substantial long-term benefits to the industry stakeholders (Boje et al 2020). These benefits include real-time monitoring and optimization of processes/ products, predictive insights into future performance to support decision-making, and predictive maintenance (Ozturk 2021).

2.1 Concept of Digital Twins uses

Within construction logistics and the industry in general, there is a growing awareness of the potential implications of DTs for the sector, essentially on how exactly DTs can lead to better processes and products. There is a need to understand the benefits of the concept in this context, and develop implementation strategies. To do that, it is necessary to understand in depth what DT could mean for construction logistics, in terms of what value it brings to the different stakeholders involved, and how those values can be realized (Bakhshi et al 2024).

Understanding what exact benefits DTs have for a context can be challenging. In the construction industry, there exists a gap between the theoretical benefits and the practicalities of DTs (Park et al 2024). This gap exists because there is no single way of defining or constructing DTs. A variety of technologies, software, and data sources can be used to construct DTs. Theoretically, this opens up limitless possibilities for where and how DTs can add value as their applications are inherently data-driven. Multiple insights can be derived from the same data sets, and data can be sourced from different sources or created using different technologies, essentially resulting in endless application possibilities. However, many of these applications of DTs are not easily feasible when it comes to practice. This complexity is attributed to the construction industry's complex social system, comprised of numerous stakeholders, each with their unique needs, objectives, and operational methods. It can be thus argued that the limits of DT benefits are shaped not just by the theoretical possibilities, but also by the characteristics of the social system it is to intervene in.

Transitioning from the broad concept of DTs to their specific applications in construction logistics necessitates a structured approach. As a starting point, a systematic framework that identifies, categorizes, and presents viable DT application areas within the construction logistics sector can be highly beneficial. As we discussed, the practical limits and benefits of DTs are not shaped by its theoretical possibilities, but rather the specific characteristics of the context it is to intervene in. As such, said framework should focus not only on the technical capabilities of DTs but also on the social context inherent to construction logistics.

2.2 Digital Twins in Urban Contexts

The DT Uses Framework for Construction Logistics aims to explore DTs in the context of construction logistics. In the following chapters, a conceptual framework is detailed, which aims to identify and analyze the various dimensions/ aspects of construction logistics and DTs that can be used to explain the relationship between the two. The conceptual framework is intended to determine how these dimensions intersect and can be represented within a singular framework to provide a comprehensive understanding of how DTs can be effectively utilized and integrated into construction logistics practices (Gehring and Rüppel 2023). In essence, data flows from the physical to the virtual, where this data is analyzed, integrated and insights are derived, which are then used to provide feedback to the physical system, essentially leading to better design, processes and operations (Figure 1).

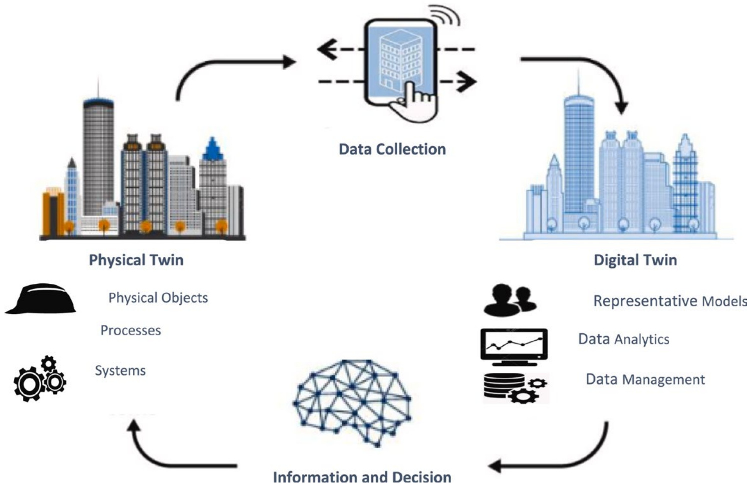

Figure 1. Digital Twins process for urban analytics (Moshood et al 2024)

3 Research Methodology: Agent Based Modelling

In order to test logistics strategies we applied a quantitative modelling approach using Python. It is based on the many available and generated geospatial datasets. This model uses agent-based approach (ABM) to simulate the behavior of construction sites, consolidation centers, and suppliers to estimate transportation emissions associated with construction to estimate emissions associated with construction logistics in metropolitan areas.

The first step in the design of the conceptual framework was to understand the various aspects of both DTs and logistics that can be used to explore and explain the relationship between the two. The stakeholder requirements for the framework give an initial idea in this regard. Four aspects related to DTs were deemed important, which includes (1) Scope of DTs, (2) DT Applications, (3) Sophistication of DT uses, and (4) Feasibility of the DT uses (Figure 2).

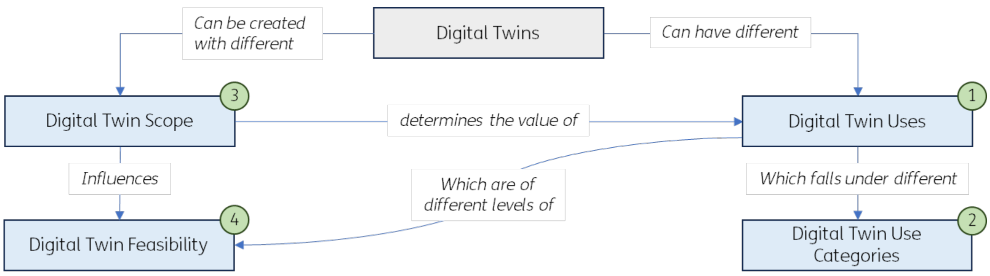

Figure 2. Aspects Framework for Digital Twins (source: LOKET project)

3.1 Modelling Digital Twins Aspects

When exploring the implications of DTs in the context of construction logistics, the questions are primarily in two directions: the value that DTs bring to the different stakeholders, and its practical feasibility. For logistics, experts highlighted critical aspects: Logistics Operation Type, Logistics Chain Management Typologies, Logistics Functions, and Stakeholders i.e. agents.

DTs are developed with a particular scope, which pertains to the 'physical system' aspect of the DT—essentially, which part of the real world is the DT replicating. It is important to recognize that DTs can take different shapes within a given context. In the context of construction logistics, for example, the scope can range broadly from the complete construction logistics network of an entire city to the more focused logistics chain of a specific project, and down to the day-to-day logistics operations within a single construction site. Understanding the scope of discussion helps to identify the relevant stakeholders and their processes to which DTs can add value to.

Within a defined scope, a DT can have various specific "DT Uses", which can be thought of as very specific application areas that the DT realizes within its scope. For instance, within the scope of a DT of a construction site, a particular "use" might involve a very targeted application, such as optimization of resource allocation in real-time.

The scope of a DT significantly influences both its technical and operational feasibility. Moreover, the technological landscape and capabilities of the stakeholders involved in creating and utilizing the DT also play an important role in determining the practicability of its various uses. This helps in both setting realistic expectations and priorities for their development and for strategizing effectively, focusing initially on applications that are more immediately achievable and gradually progressing towards more complex, sophisticated uses as the technological and operational landscapes evolve.

3.2 Modelling Logistics Aspects

Construction logistics involves a range of activities and a complex ecosystem of stakeholders, each playing a specific role in the logistics supply chain (Table 2). In addition, stakeholders play a role as developers, data suppliers, and users of DTs.

Table 1. Agents representing Stakeholders in the construction supply chain (De Bes et al 2018)

#	Agents
1	Supplier
2	Transport firm or Logistics Service Provider
3	Construction Site/ Main Contractor
4	Sub Contractor
5	Municipality
6	construction center

Efficient coordination between these different actors is essential to guarantee the timely and seamless progression of construction tasks and processes. Logistics chain management involves the activities that are integral to ensuring this coordination. Fundamentally, chain management can take two broad forms: vertical and horizontal logistics. In vertical logistics, a single entity oversees the entirety of the supply chain activities, from the procurement of materials to the final stages of construction. Horizontal logistics, on the other hand, is characterized by some agreed level of cooperation among various entities at the same level of the supply chain.

Regardless of the specific typology adopted within the logistics chain, there are several crucial logistics functions integral to its effective operation, all of which demand a high level of coordination among involved parties. A preliminary list of these functions, derived from previous research, is presented in Table 2. It is important to note that this list is not exhaustive but an initial outline of key logistical functions. These functions represent direct application areas for DTs.

Table 2. Logistics Functions (De Bes et al 2018)

#	Logistics Function	Description
1	Transport Planning	Transport planning in construction flows to and from the construction project
2	Construction/ Production Planning	Linking construction planning, transport planning, and production planning
3	Asset Planning of construction equipment	Planning of availability / deployment of construction equipment, e.g., construction cranes
4	Construction tickets and scheduling delivery time windows	Planning of delivery times and construction tickets
5	Inventory Space Planning	Inventory management at construction site or consolidation center
6	Consolidation of Construction flows	Bundling / consolidation planning of transport flows from consolidation center to construction site
7	day/ work package planning	Planning / compilation of work packages based on construction activities and planning
8	tracking and tracing	Real-time tracking and tracing of transport movements
9	performance measurement/ monitoring	Performance measurement of construction logistics: emissions, costs, full truck loads, productivity, etc.
10	road capacity management	Planning and allocation of limited road capacity to target groups

4 Modelling Case Study and Findings

From a logical perspective, four DT levels can be identified for logistics activities and analytical functions of the modelling. These include the (1) Network level, for instance, a municipality with multiple projects and traffic network; (2) the individual Construction Site level; (3) the Supply Chain level, referring to the logistical network specific to a single project, and (4) the Monitoring level capturing data, calculating and visualizing economic and environmental effects. It is important to note that these levels are derived from existing modelling and data approaches, and may not yet fully capture further data, such as data that is produced by generative modelling or AI. Furthermore, as yet, the approach excludes considerations of multi-project collaborations of material deliveries. However those considerations would introduce potential further benefits of DT applications.

4.1 Network or Urban Area Level

To establish logistics requirements for construction projects and ensure uninterrupted traffic flow, municipalities have to make numerous decisions. A Network-level DT can significantly aid this process. Such a DT can provide a comprehensive overview of both current and future construction projects, enabling decision-makers to visualize the entire project landscape within their municipality. The DT can be enriched with additional data such as project statuses and logistics movements to and from the sites. Integrating this with real-time or historical traffic data allows for the analysis of traffic patterns over time and space, enhancing the understanding of traffic distribution within the municipality (Brusselaers et al 2024). Moreover, the addition of simulation capabilities expands its use to spatial-temporal analysis to test what-if scenarios such as the impact of a new construction project on traffic (Brusselaers et al 2024). Through these DT uses, municipalities can adopt a proactive, data-driven approach to mobility planning at the network level, potentially reducing traffic congestion and disruptions caused by construction logistics (Figure 3).

Figure 3. City level Digital Twin, base model including traffic data made available by municipality (case Utrecht)

4.2 Construction Site Level

Once a construction project is underway, a Construction Site DT offers numerous uses from planning to operations. For example, during the planning phase, a beneficial DT Use is Site Layout Planning, which facilitates the organization of various site elements, including the placement of inventory, crane positioning, material drop-off points, and the allocation of necessary mobility resources (Amiri et al 2023). As the project progresses, real-time data gathered from various sensor technologies—such as RFID tags, drones equipped with cameras, and Bluetooth beacons—can support the DT in Resource Status Monitoring, allowing for real-time tracking of resources on-site (Jiang et al 2021a). This can be further enhanced by integrating it with predictive algorithms, aiding in the early identification of potential bottlenecks (Jiang et al 2021a). Additionally, real-time progress data, when synced with project timelines, can be used to automate the call-offs for materials, ensuring the timely availability of necessary resources (Jiang et al 2021a) (Figure 4).

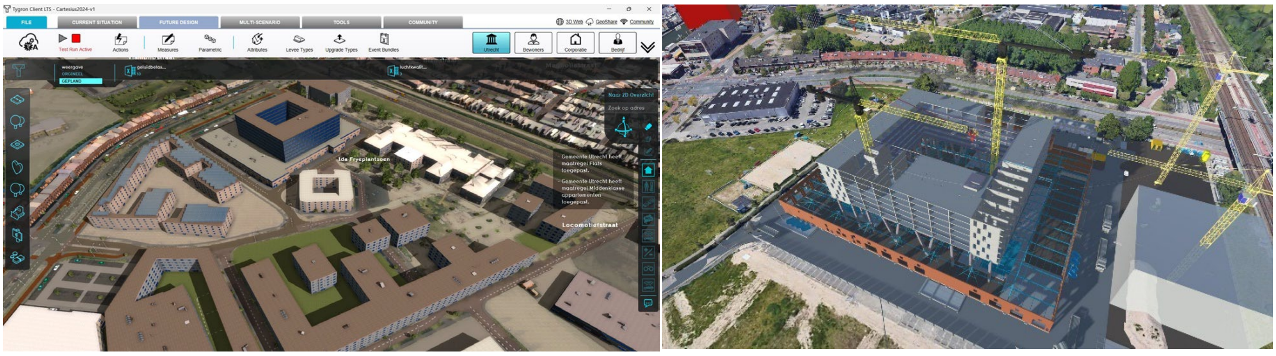

Figure 4. Construction site in area model, including buildings under construction and future buildings (Case Utrecht)

4.3 Supply Chain Level

Coordinating the supply of materials to a construction site involves managing inventories, located on-site or at consolidation centers. In this context, a DT focused on inventory can provide significant benefits. For instance, a range of sensor technologies, including RFID tags and drones, can be utilized for real-time inventory management, enabling the tracking of material stock and flows (Qiu et al 2023). This data can be further leveraged for forecasting future inventory requirements by integrating inventory data with construction schedules (Qiu et al 2023), which can also be extended to bottleneck analysis for construction progress by examining inventory levels. By doing so, it ensures a smooth and efficient supply of materials, minimizing delays and optimizing the construction process. Also logistics alternative scenarios and the effects could be tested and simulated (Figure 5).

Figure 5. Modelling the last mile of supply chain to construction site, including traffic analysis, and modal shift scenario comparison when using ships instead of trucks for construction transport (Stikstof is Dutch for NOx) (Case Utrecht)

4.4 Monitoring Level

Lastly, the supply chain scope of DTs can assist in tracking the flow of materials. This is particularly valuable in scenarios where a construction site receives materials from multiple suppliers. By employing a DT in the supply chain context, stakeholders can gain a comprehensive view of material movements from multiple stakeholders through a blockchain-enabled network, enhancing coordination and efficiency (Jiang et al 2021b). This capability can also pave the way for the integration of smart contracts, automating and securing transactions based on predefined rules and real-time data (Jiang 2021b). During the delivery of materials, such DTs can also assist in dynamic route planning, which actively identifies potential delay risks and suggests alternative routes (Lee and SangHyun 2021), which can be helpful for effect mitigation (Figure 6).

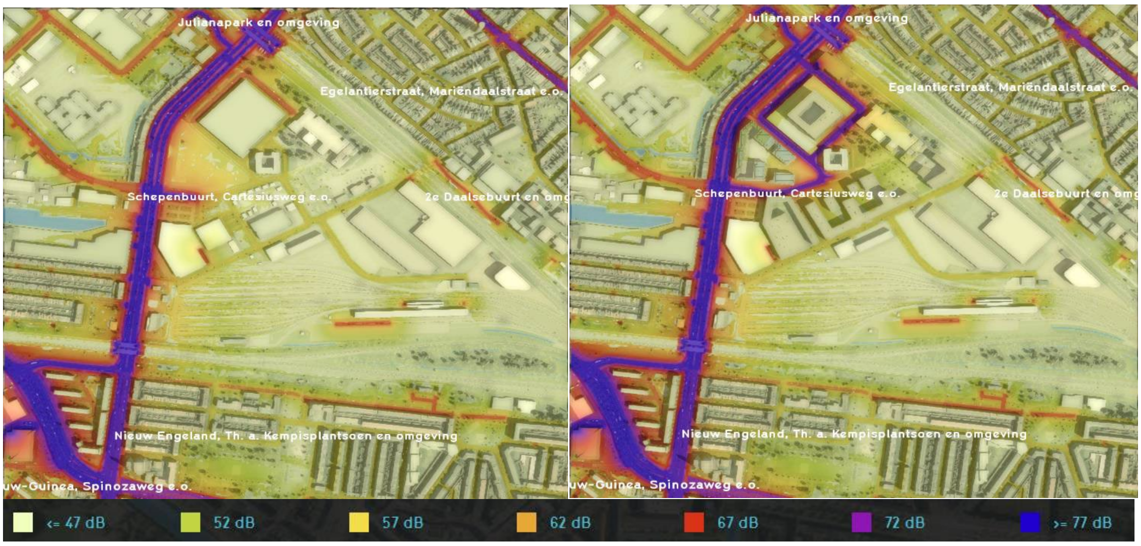

Figure 6. Visualizing noise levels on last mile to construction site, before versus during construction (Case Utrecht)

5 Discussion

The multilevel spatio-temporal geographical modelling as presented in this paper increases the capabilities of DT to a wider range with more insights for users. In this case insights have been demonstrated in the wider transport network around and to construction site and the environmental impacts. The scalability of such models including other construction types and infrastructure projects would be beneficial to perform more comprehensive spatial analyses of more aspects and effects in a wider urban area. However data availability and model complexity poses challenges for model developers and data suppliers (Gehring & Rüppel 2023).

Firstly, the quality of available data is limited. Some of the data include data that relies on expert estimations rather than open and widely available data of building materials and logistics details, such as trucks load percentages for materials and supplier locations. Additionally, mismatches in material categories between construction and demolition sites in circular scenarios, and potentially inaccurate emission coefficients for ships compared to trucks, further limit the model accuracy. Data needed for estimation of urban impacts is often not readily available and needs preparation (Guerlain et al 2019).

Secondly, limitations have been found to how the model estimates the impacts of logistics on the environment. While the model estimates effects such as, noise and emissions, it does not include, for example, accounting for potential embodied emissions savings, when switching to biobased buildings. Nor does it include other advantages of modular and lighter construction materials, such as the reduction of road damage caused by heavy freight.

6 Conclusions and Further Research

This paper has presented a novel multilevel agent-based modelling approach for construction logistics, based on DTs within the dynamic specificities of construction logistics. The modelling approach has bridged the divide between DTs and construction logistics. By systematically categorizing the various dimensions of DTs and logistics, it has provided a structured approach to identifying DT applications that enhance insights in the operational and environmental performance of construction logistics and the improvement of the performance.

However the modelling of the interconnected agents on the respective municipality network, construction site, supply chain and monitoring levels has faced a few challenges. The network DT, offers municipalities an overview of construction projects and traffic flows, facilitating proactive traffic planning and requirement setting regarding construction logistics. Construction site DTs can enable precise planning and real-time resource monitoring. Supply chain DTs can streamline material management and optimize delivery routes, and last mile traffic implications. The monitoring DT includes parameters and algorithms to calculate and visualize environmental effects of transport movements. The complexity of the multiple interconnections between the levels of the DT has contributed to reduced levels of transparency of the calculated environmental effects.

Next the integrated approach has to be developed through wide application to larger numbers of different practical cases to validate the method. This involves a thorough analysis of different specificities of construction logistics, such as detailed activities involved, responsible stakeholders, their technological landscape and process improvement requirements, and organizational implications of DTs. This complexity can reduce the feasibility of DT uses for such analyses.

7 Acknowledgement

This paper is based on the Dutch national TKI Dinalog research project called 'LOKET'. The project aims to investigate the role that DTs can play in different forms of supply chain management based on the availability and use of real-time data from construction sites and the logistics chain. The paper explores the possible applications of DTs for construction logistics, followed by the development of case-specific demonstrators of DT uses.

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