

Conceptual Digital Twin uses framework for construction logistics

LOKET

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1 Introduction

1.1 The spotlight on construction logistics

The Netherlands is witnessing a remarkable spike in demand for construction projects and related activities. This surge is driven by diverse challenges, from the renovation and replacement task of the country's road, rail, and water infrastructure, to the renovation of existing building stocks, and the development of new residential areas. This situation highlights the substantial volume of construction projects and activities that are anticipated to be undertaken in the coming years.

While there is the sheer volume of activities on one side, there is also the necessity to maintain the environmental sustainability of these projects on the other. There is thus also an urgent requirement to minimize the environmental impacts of construction projects, with a particular emphasis on reducing nitrogen emissions, which remains a critical concern for the sector. Moreover, it is non-negotiable that this significant scale of construction does not compromise the safety, liveability, and accessibility of the Netherlands. These scenarios emphasize the importance of refining, redefining, and/ or reorganizing multiple aspects of construction. With regard to reducing nitrogen emissions and ensuring safety, liveability, and accessibility, construction logistics comes into sharp focus. The spotlight it is on is unavoidable.

Logistics serves as a fundamental aspect of construction, playing an important role in the success of any project. It includes the processes that ensure the availability of necessary resources on time for construction activities. This includes, among other tasks, planning and executing the delivery of resources to the construction site, managing these resources on-site, and handling the flow of waste from the site [1].

Construction projects typically involve a myriad of (sub)contractors, 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 continuous [2]. Moreover, a significant portion of construction projects are concentrated in major urban areas [2]. The extensive logistics associated with these projects can significantly impact city traffic, leading to congestion that affects the cities' liveability and accessibility while also increasing emissions due to the resulting traffic jams. Given these critical impacts, it is not a surprise that logistics is in the spotlight for urgent action.

1.2 Towards smart and sustainable logistics

The critical role and impact of construction logistics have undoubtedly driven significant research efforts aimed at improving it. For example, studies have demonstrated the advantages of smart logistics solutions in construction, such as the implementation of integrated chain management (control and orchestration) and the utilisation of Bouwhubs (construction hubs) [1]. These strategies have been shown to significantly reduce the volume of transportation movements to sites, which in turn leads to decreased emissions [1].

Despite the promising outcomes presented by these studies, the widespread adoption of these sustainable solutions and interventions within the industry remains limited due to existing organisational and technical barriers.

Organisational barriers include outdated tendering processes, a lack of coordination agreements among the various parties involved, and a prevailing project-specific mindset within the construction industry [2]. These factors often limit stakeholders' capacity to focus beyond ensuring the timely availability of necessary resources for individual projects, impeding the implementation of broader logistics improvements. Technical challenges further complicate the situation. The involvement of numerous parties in the logistics chain and the persistence of (so-called) traditional working methods lead to a lack of transparency in the process and inadequate data management practices. This hinders coordination among logistics participants and limits the ability to derive insights and learn from data throughout these processes [1].

Even when smart and sustainable logistics practices are incorporated during tendering or planning phases, their monitoring during execution is frequently lacking [1]. This isn't 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 optimisation doesn't necessarily translate to overall logistics chain efficiency.

1.3 Context of the report

Various studies on sustainable logistics advocate for a move towards more cohesive chain management approaches, emphasising improved data management and utilisation [1]. Enhancing transparency and fostering better coordination within the chain are also critical steps. Digital twins offer a promising solution in this regard. A Digital Twin is a dynamic virtual representation of an entity or process, that utilises real-time operational or behaviour data to enable monitoring, analysis, and optimization of the entity or process.

The LOKET project explores the role of Digital Twins in construction logistics. It aims to understand how Digital Twins can benefit various chain management strategies, identify the conditions and challenges for their successful development and implementation, and determine the role of standards in this process.

This report, as part of the TKI LOKET project, introduces a conceptual framework designed to bridge the gap between the theoretical potential of Digital Twins and their practical application in construction logistics. By providing a methodology to identify relevant and feasible Digital Twin applications, the conceptual framework sets the foundation for assessing the potential uses of Digital Twins within the construction logistics sector. The goal of this report is to present this framework in detail, explaining its components and illustrating how it can be applied to real-world cases. By doing so, we aim to set the foundation for assessing the potential uses of Digital Twins in construction logistics and to guide stakeholders in utilising this technology to improve the efficiency and reduce the negative impacts of the construction logistics. This report is made in cooperation with the University of Twente by combining knowledge from both parties into this report.

The report is structured as follows. In the next chapter, we begin by explaining the concept of Digital Twins through their defining characteristics. Then, we define the DT Uses Framework and explain its various components in detail.

Following that, we present some potential examples of Digital Twin uses relevant to construction logistics, derived through the framework. Lastly, we provide an outlook on how the framework can be further detailed and developed in the different cases within the LOKET project.

2 Digital Twin uses framework

2.1 Digital Twin and its' characteristics

A Digital Twin is a dynamic virtual representation of a physical asset or process, in which the physical and virtual counterparts interact with each other to optimise the performance or the operations of the asset or process [3]. Broadly, it consists of three parts as illustrated in Figure 1. In essence, behaviour or operational data is collected from the physical and sent to the virtual, where this data is analysed and insights are derived, which is used to provide feedback to the physical system, essentially leading to better design, processes, operations, and reuse of assets.

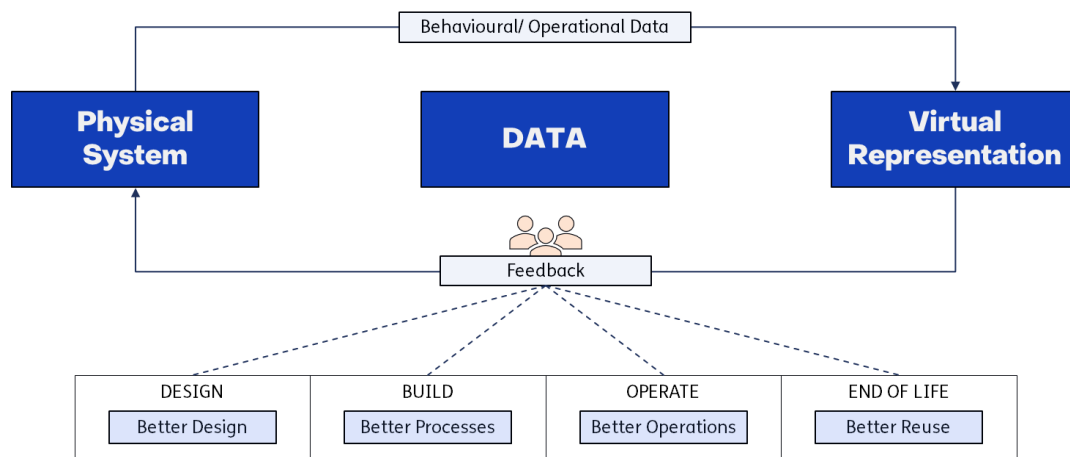


Figure 1: Parts of Digital Twin

There are numerous definitions and conceptualisations of Digital Twins, each offering unique perspectives. Important to note that our goal here is not to discuss and debate all of these varied definitions. Instead, we take a comprehensive, inclusive perspective.

This perspective can be explained through the following defining characteristics of a Digital Twin (based on [4]):

- (1) Digital Twin is a **real (/right) - time and smart** virtual representation of a physical system
 - At its core, a Digital Twin offers a dynamic and intelligent virtual representation of a physical system—this could be an entity, a process, or a combination of both. The dynamic nature and embedded intelligence of Digital Twins are important to be understood. Unlike a static description of a physical system, such as a BIM model, a Digital Twin continuously evolves, reflecting real-time changes in relevant parameters of the physical system within its virtual counterpart.

- We say the changes in the physical system are reflected in the virtual system in real-time. However, this does not imply instantaneous updates within fractions of a second. Rather, it means that updates occur at a frequency that is appropriate and sufficient to meet the user's specific needs. In some cases, these could be (near) real-time (for instance think of functionalities relevant to safety) and in some cases, they could be 24 hours (for instance think of the end of the day performance reports). In the end, it depends on the intended purposes of the Digital Twin.
 - A virtual representation that reflects the actual behaviour of a physical system is undoubtedly valuable. However, a Digital Twin is not (and should not be) merely just a description of reality. Its true potential lies in being prescriptive—enabling users to understand the changes in behaviour (in ‘right’ time), uncover the reasons behind those changes, and determine their implications for informed decision-making (and beyond).
- (2) The **virtual representation does not have to be in 3D**:
- A Digital Twin is fundamentally a virtual representation of a physical system, but this ‘representation’ does not need to be in 3D, which is often the first association when one thinks of the concept. For instance, when discussing the Digital Twin of a construction site, it doesn’t necessarily imply having a fully detailed 3D model of the site being updated in real-time or near-real-time. This notion can often lead to unnecessary complexity.
 - A Digital Twin begins with its purpose; what the user needs it to achieve. The representation in the virtual should be tailored to meet those specific needs. While 3D visualizations can be highly effective in certain contexts to enhance understanding, they are not always essential. In many cases, dashboards or KPIs may serve the purpose just as effectively as a 3D model. Think for example the construction site again, if the (only) purpose of the Digital Twin is to track progress in real-time, this can be represented using parameters such as completion percentages, schedule adherence, or resource utilization—none of which necessarily require a 3D model.
- (3) It combines **static data with dynamic data**:
- Digital twin's essence lies in merging two types of data: static data and dynamic data. Static data includes foundational information, such as BIM models or logistics schedules, while dynamic data reflects real-time changes, such as GPS locations or sensor readings.
 - By integrating these data types, Digital Twins try to offer a continuously updated representation of the physical system. This integration equips users with information that can enhance decision-making, like for instance identifying disruptions in a process early, enabling interventions to be proactive rather than reactive.
- (4) It enables **bi-directional** communication:
- The interventions that we just mentioned are why we ought to develop Digital Twins in the first place. It is not just to have a virtual monitoring system; rather, it eventually evolves into (or should evolve into) something that participates in the operations by providing feedback.
 - This feedback can either be direct communication between virtual and physical - such as sending instructions to the physical system through actuators (for instance think of automated traffic lights)—or indirect, by offering data-driven insights to support human decision-making.
 - In essence, this feedback loop can operate with or without human intervention. Ideally, Digital Twins provides outputs that are useful to intervene in the physical system’s decision-making.

(5) Not a monolith but a [network](#):

- A Digital Twin should not be perceived as a single, all-encompassing system. While it might be technically possible to create such a system, it would likely result in an overcomplicated, monolithic structure that is difficult to develop, maintain, and scale. Instead, a Digital Twin should be envisioned as a network—a web of semantically linked data, models, and technologies working together.
- The essence of a Digital Twin lies in integration. By connecting diverse systems, sometimes managed by different parties, and ensuring they work together, the twin can effectively represent and manage the physical counterpart without being a monolithic structure. However, achieving this level of integration requires careful planning and specialized expertise in system integration.

(6) Generating [Value Across Lifecycle Phases](#):

- Ultimately, the purpose of a Digital Twin is to create value. By enhancing transparency and providing actionable insights, it improves existing systems and processes. However, as with its other characteristics, it is essential to emphasize what a Digital Twin should evolve into. Over time, it becomes a tool for continuous learning, enabling the application of lessons to future projects or phases. This is one of the key value propositions of Digital Twins.
- Through simulations and "what-if" analyses using real-time data, Digital Twins offer predictions about future lifecycle phases. They can also analyse what went wrong in past phases, facilitating improvements in future processes, products, or lifecycle stages. This ability to bridge past insights with future planning is what makes Digital Twins such a valuable tool, especially in the construction sector where learning from the past is arguably not a standard practice.

2.2 Digital Twin uses framework

2.2.1 Concept

We have outlined the characteristics of a complete Digital Twin—one that, in essence, could handle everything. But this leads to an important question: where do we even start when it comes to its development? In the construction logistics sector (and the broader construction industry), there is growing curiosity about the potential implications of Digital Twins, particularly how they can lead to "better" processes and products. To bridge the gap from an "idea with potential" to practical implementation strategies, it is important to explore what Digital Twins can specifically mean for construction logistics, focusing on the value they bring to different stakeholders.

Defining the exact benefits of Digital Twins in a given context is challenging. This is because, theoretically, there are limitless possibilities for how and where Digital Twins can add value, as their functionalities are inherently data-driven. Multiple insights can be derived from the same datasets, and data can be sourced or created using different technologies, enabling endless potential applications.

However, many of these theoretical functionalities are not easily achievable in practice of the construction industry. This complexity arises from the construction industry's intricate social system, which is inherently project-based and consists of numerous stakeholders, each with distinct needs, objectives, operational methods, and technological landscapes - the same aspects that need to be aligned and integrated in one way or another to realise Digital Twins. This is a significant challenge.

Therefore, the value (benefit vs effort) of Digital Twins is shaped not only by their technical potential but also by the social and organizational context in which they are deployed.

This is where the DT Uses Framework is of value. To move from the broad concept of Digital Twins to specific applications within construction logistics, a structured approach is essential, one which accounts for both the technical capabilities of Digital Twins and the social context of construction logistics. The DT Uses Framework [4] is such a tool that brings together the features of Digital Twins with the specificities of their application context. By bringing together these perspectives, the framework helps clarify the potential implications of Digital Twins for a given context. It identifies the value Digital Twins can deliver, the stakeholders who benefit from it, and an understanding of how these values can be realised.

As the first step toward developing a complete DT Uses Framework for construction logistics, this report outlines a conceptual framework. The aim of this framework is to provide a foundation that can be further developed and refined within the context of the LOKET project. By applying this framework to different use cases within the project, we aim to gain deeper insights and iteratively enhance our understanding. Ultimately, this process will help define what Digital Twins mean for construction logistics, providing a clear and practical pathway for their application in the sector.

2.2.2 Interpretation of the framework

The DT Uses Framework is a tool designed to identify and prioritize the most relevant, high-potential, and feasible applications (Uses) of Digital Twins within a specific context. The Conceptual DT Uses Framework for construction logistics is presented in Table 2, with interpretation instructions illustrated in Figure 2. The logic behind the design of the framework, including the stakeholder requirements and several factors that influenced the design decisions, are explained in Appendix A. In this appendix, different elements that are shown in Figure 2 below are thoroughly explained.

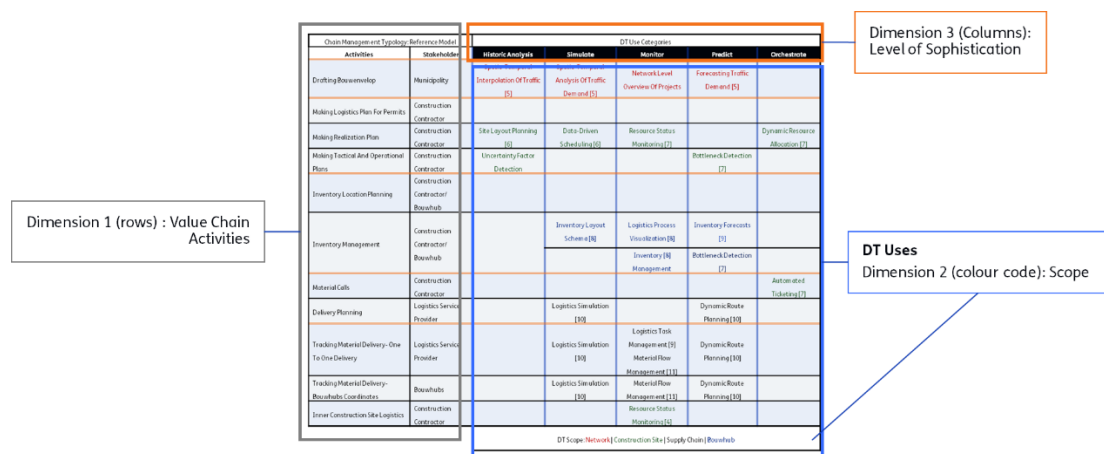


Figure 2: Legend to DT Uses

(Note: For better understanding, please refer to the DT Uses Framework in Table 2, form a first impression, and then return to this section)

At its essence, the framework serves as a collection of Digital Twin functionalities, systematically identified and structured.

The idea behind the framework is to take the expansive concept of Digital Twins and break it down into smaller, accessible components in the form of specific functionalities tailored to specific users (DT Uses), and present it to the stakeholders in a simple, easy-to-understand manner. In this way, the core message of the framework lies in the **DT uses**—specific functionalities of Digital Twins that are both relevant and feasible for a given context.

This level of detail and the framework's perceived simplicity are achieved through its four **dimensions**. While the framework appears straightforward, its simplicity comes from 'hiding' detailed theoretical and practical analyses within these dimensions. This analysis and thus the dimensions define the criteria for effectively selecting and prioritizing DT uses. The dimensions are explained further below.

Dimension 1: Value chain activities

The first dimension focuses on the value chain activity, addressing the critical question of where a Digital Twin can be used and by whom. To create a framework with a high level of detail, several key elements are (to be) considered within this dimension. First, it examines the different activities within the value chain, alongside the strategic goals (or values) of the value chain. This involves analysing how these strategic goals/ values translate into specific operational activities. Additionally, the technical landscape supporting these activities is assessed to identify technical opportunities and limitations regarding Digital Twins. The bottlenecks, needs and opportunities of the responsible stakeholders are also assessed. Together, this analysis helps define the functional requirements of Digital Twins, essentially determining what functionalities of Digital Twins are required and what is (organisationally and technically) feasible within the given context.

Dimension 2: Scope

The second dimension focuses on the scope of the twin. This dimension addresses the question of what can actually be twinned—essentially, the physical system that is being represented. For example, a Digital Twin for logistics is not a singular, unified entity but rather a combination of multiple, distinct scopes that work together to achieve the overall objective. For example, in a logistics scenario involving the transport of materials from the supply chain to a construction site via a construction hub, at least four distinct scopes can be identified: the supply chain, the construction hub (bouwhub), the construction site, and the transport network, as illustrated in Figure 3.

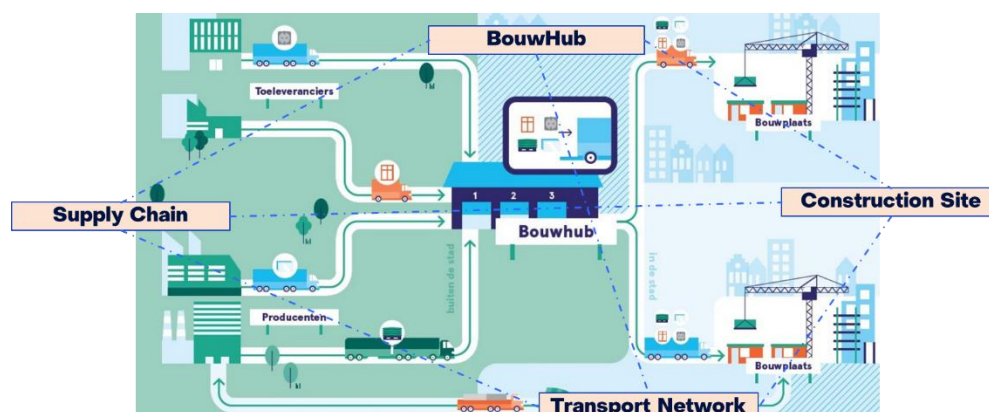


Figure 3: Example DT Scopes (layered above illustration from SmartwayZ.NL)

Scopes can also be defined at different levels of detail. For instance, the supply chain and transport network scopes might be combined into a single larger supply chain scope.

Such decisions are essentially design choices for the Digital Twin, (to be) made based on technical and operational feasibility and specific project requirements. The architecture of a Digital Twin, which includes considerations like data sources, communication protocols, system outputs, and user interactions, is inherently shaped by the specific scopes it represents. It is thus important to select scopes that are practical and achievable.

Dimension 3: Sophistication

The third dimension focuses on the sophistication of Digital Twins, which categorizes the type of DT Uses and, in a way, influences their complexity. While the potential applications of Digital Twins are vast, they generally align with one of five broad categories of sophistication as illustrated in

Figure 4. These are (1) Historical Analysis, (2) Simulation/ Mimicking, (3) Extraction/Monitoring, (4) Prediction, and (5) Orchestration.

These categories, which have been identified through literature [4], align with the intrinsic characteristics and functionalities of Digital Twins, such as data-driven insights, optimization through simulation, real-world sensing capabilities, predictive analytics, and the orchestration of complex systems. This categorization aids in understanding the "type" of value the particular Digital Twin use is offering to the stakeholders and also gives an idea of the complexity of realising the use.

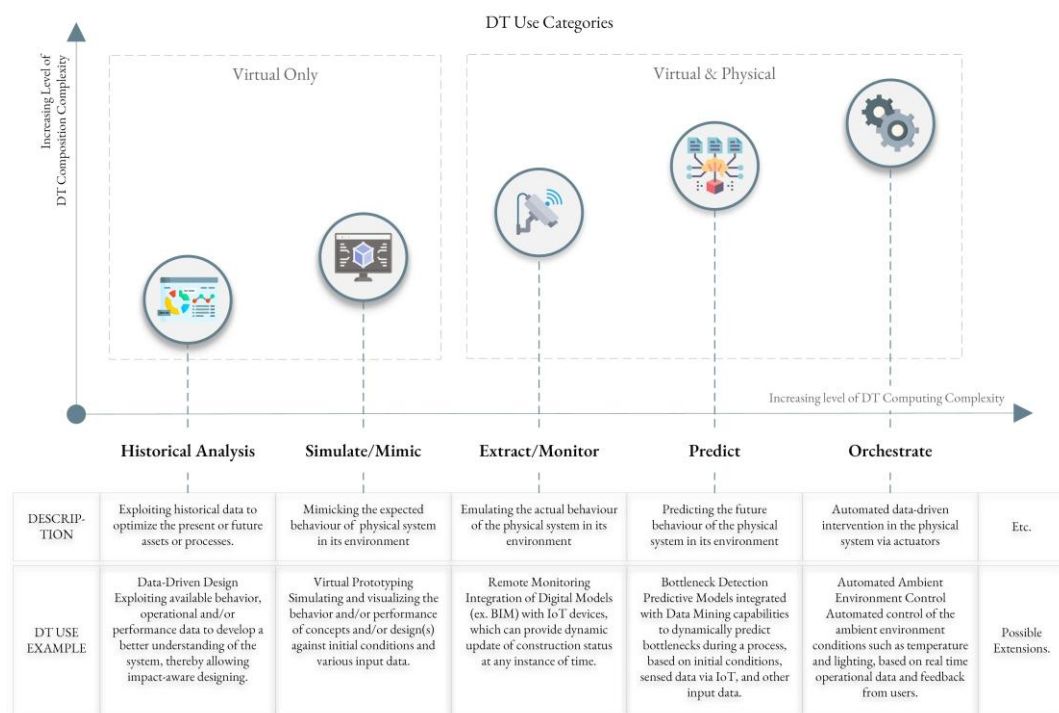


Figure 4: Digital Twin Use Sophistication Levels

Dimension 4: Chain management typologies

Lastly, specific to construction logistics, one more dimension needs to be considered. These are the chain management typologies. Logistics chain management involves the activities that are integral to ensuring coordination between the different actors in a logistics chain. It can manifest in various **chain management typologies** [5]. These are essentially the organizational structures adopted to manage and facilitate these logistics operations.

Some of these typologies require vertical coordination, while some require horizontal coordination. The specific structure of a logistics chain, therefore, hinges on the chosen typologies, which are detailed in Table 1.

Table 1: Different Chain Management Typologies [5]

#	Chain management typology	Description
1	Reference model	No governance - current situation (reference)
2	Offset Model (Verrekening)	Offsetting of delivered transports – collaborative association of logistics service providers
3	Consensus Model (Consultation)	Cooperation structure with equal say for all partners
4	Concession Model	One logistics service provider (temporary, via concession) conducts the supply chain governance in an area
5	Government model (overheidsmodel)	Government conducts governance
6	Waterway	Supply chain governance on (waterway) road capacity/traffic management from the (waterway) road manager
7	Vertical - contractor	The governance lies with one party from the vertical chain (producer/supplier, logistics service provider, contractor)
8	Vertical - LSP	
9	Vertical - supplier	

From the perspective of DT uses, these typologies become key in determining the scope and users of the Digital Twin. The factors that are to be analysed in Dimension 1, such as the activities, information needs, user requirements, bottlenecks, and other factors that determine the Digital Twin Functional requirements, all vary based on the typology in place. Further, the choice of (the level of detail of) Digital Twin scope explained in Dimension 2, also is dependent on the typology. This means that DT uses identified as relevant and feasible for one typology might not be applicable or feasible in another. Therefore, chain management typologies are an essential dimension to consider when applying Digital Twins in construction logistics.

Table 2: Conceptual DT uses framework for construction logistics

Chain management typology: reference model		DT use categories				
Activities	Stakeholder	Historic analysis	Simulate	Monitor	Predict	Orchestrate
Drafting Bouwvelop	Municipality	Spatio-temporal interpolation of traffic [6]	Spatio-temporal analysis of traffic demand [6]	Network level overview of projects	Forecasting traffic demand [6]	
Making logistics plan for permits	Construction contractor					
Making realization plan	Construction contractor	Site layout planning [7]	Data-driven scheduling [7]	Resource status monitoring [8]		Dynamic resource allocation [8]
Making tactical and operational plans	Construction contractor	Uncertainty factor detection			Bottleneck detection [8]	
Inventory location planning	Construction contractor/ Bouwhub					
Inventory management	Construction contractor/ Bouwhub		Inventory layout scheme [9]	Logistics process visualization [9]	Inventory forecasts [10]	
				Inventory [9] management	Bottleneck detection [8]	
Material calls	Construction contractor					Automated ticketing [8]
Delivery planning	Logistics service provider		Logistics simulation [11]		Dynamic route planning [11]	
Tracking material delivery – one to one delivery	Logistics service provider		Logistics simulation [11]	Logistics task management [10] Material flow management [12]	Dynamic route planning [11]	
Tracking material delivery- bouwhubs coordinates	Bouwhubs		Logistics simulation [11]	Material flow management [12]	Dynamic route planning [11]	
Inner construction site logistics	Construction contractor			Resource status monitoring [4]		
DT Scope: Network Construction site Supply chain Bouwhub						

2.2.3 Example Version

These different dimensions define the scope for identifying the key elements within the framework; the DT Uses relevant to the particular case. The framework thus facilitates an understanding of what a Digital Twin is for a specific context through its uses. Moreover, it provides insight into the complexities associated with different DT uses. By doing so, it acts as a decision-making mechanism, enabling stakeholders to prioritize applications and design a structured development pathway for their Digital Twins. This includes determining which DT uses to start with and how to scale them up effectively over time.

An example version of the DT Uses Framework for construction logistics is given in Table 2. It is important to emphasize that the analysis of the dimensions and the identified DT uses in the present framework are solely based on literary sources. The primary purpose here is to demonstrate the application of the framework, thereby enhancing understanding of its layout and serving as a foundation for more in-depth exploration and detailing.

In the present version, four Digital Twin scopes (Dimension 2) are considered by referring to the available literary sources. These are (1) network, for instance, a municipality with multiple projects and traffic network; (2) individual construction sites; (3) the supply chain, referring to the logistical network specific to a single project; and (4) bouwhub, covering material storage (and management) in construction hubs (Bouwhubs). It's important to note that these conceptual scopes are derived from existing activities recorded in various literature and may not yet fully capture the exact picture of practice. Furthermore, this discussion is framed within the reference model typology, thereby excluding considerations of cross-project collaborations in material delivery. Within these defined scopes, a variety of DT Uses have been identified through literature, as explained below.

Network (area oriented)

To establish logistics requirements for construction projects and ensure uninterrupted traffic flow, municipalities have to make numerous decisions. A Network-level Digital Twin can significantly aid this process. Such a Digital Twin can provide a comprehensive overview of both current and future construction projects, enabling decision-makers to visualize the entire construction activities landscape within their municipality. The Digital Twin 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 [6]. 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 [6]. Through these Digital Twin 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.

Construction site (logistics related to on-site construction)

Once a construction project is underway, a construction site Digital Twin 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 [7]. 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 Digital Twin in resource status monitoring, allowing for (near) real-time tracking of resources on-site [8].

This can be further enhanced by integrating it with project schedules and predictive algorithms, aiding in the early identification of potential bottlenecks [8]. Additionally, real-time progress data, when synced with project timelines, can be used to automate the call for materials (material ticketing), ensuring the timely availability of necessary resources [8]. Note that these examples are some general practically feasible examples derived from literature. How it relates to the construction logistics context, which is characterised by the presence of numerous (sub) contractors and suppliers, is still to be explored, which will be done when the framework is further detailed.

(Vertical) Supply chain of individual project

The supply chain scope of Digital Twins 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 Digital Twin in the supply chain context, stakeholders can gain a comprehensive view of material movements from multiple stakeholders through, for instance, a blockchain-enabled network, enhancing coordination and efficiency [10]. 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 [10]. During the delivery of materials, such Digital Twins can also assist in dynamic route planning, which actively identifies potential delay risks and suggests alternative routes to deliver on time [11], which can be particularly helpful for just-in-time delivery situations.

Bouwhub

Coordinating the supply of materials to a construction site involves managing (local) inventories, whether located on-site or at construction hubs. In this context, a Digital Twin 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 within the bouwhubs, enabling the tracking of material stock and flows [9]. This data can be further leveraged for forecasting future inventory requirements by integrating inventory data with construction schedules [9], which can also be extended to bottleneck analysis for construction progress by examining inventory levels within the bouwhubs. By doing so, it ensures a smooth and efficient supply of materials, minimizing delays and optimizing the construction process.

As previously discussed, these examples are simply an overview of potential application areas. An in-depth analysis of practical cases is required to further detail the DT Uses reflecting the actual needs and conditions of construction logistics.

2.3 Outlook on detailing the framework

The current framework is developed mainly based on theoretical underpinnings and some practical insights drawn from previous studies. To refine and detail this framework, it is essential to analyse specific case studies. Here we explain how such a framework can be developed for different cases within the LOKET project.

To effectively fill out the framework, begin by defining the chain management typology (Dimension 4) relevant to the case (Refer to table 1 for different chain management typologies). This typology influences the scope, applicability, and feasibility of Digital Twin uses, affecting scope selection, stakeholder engagement, and potential constraints. Assess the implications of the typology on the Digital Twin implementation. Consider how the typology influences the physical systems that can be twinned, who needs to be engaged in the Digital Twin project, and any organizational or technical constraints or opportunities that may arise.

Next, analyse the value chain activities (dimension 1) to identify where and by whom Digital Twins can be used. List relevant activities, and align them with strategic goals like productivity or sustainability. Assess the needs and bottlenecks of stakeholders responsible for these activities by identifying their information requirements and the challenges they face. Evaluate the current technical landscape, including technologies in use, opportunities for improvement, and technical constraints that exist. The key questions here thus are what are the (key) activities in the chain, who are responsible for these activities, how are these activities performed now, what technologies are used, what are the information requirements, what are any present bottlenecks and improvement opportunities, etc. This analysis will help define the functional requirements of Digital Twins, determining what functionalities are required and what is feasible within the context.

Then, identify and define the DT scopes (dimension 2) by specifying the physical systems that can be twinned, such as the supply chain, construction hub, or transport network. Decide on the level of detail, basing these decisions on technical and operational practicality, while also ensuring that the scope aligns with the chain management typology identified earlier.

With these dimensions established, and DT functional requirements defined, identify potential DT Uses relevant for the different activities. Brainstorm Digital Twin functionalities that address stakeholder needs and align with strategic goals. Literature review (using functional requirements as keywords), and expert discussions help in this analysis. Classify these uses using the sophistication levels (dimension 3) and document them in the framework.

Evaluate the relevance and feasibility of each DT Use to ensure they address the needs of the activities and are achievable within current technical and operational constraints. Prioritise high-value, feasible applications that align closely with (short-term and long-term) strategic objectives and stakeholder needs, updating the framework as necessary. The DT uses can then also further be categorised into near and far future uses based on the technical landscape and other organizational considerations (such as complexities surrounding data sharing between different companies). Review the completed framework with key stakeholders and refine it based on feedback.

By following these steps, different cases can effectively utilize the DT uses framework to identify and prioritize Digital Twin uses that are tailored to the specific needs of the particular case.

2.3.1 Effect of chain management typologies on framework

As discussed, chain management typologies have a significant effect on the DT uses framework by shaping the selection and applicability of Digital Twin uses within construction logistics. The typology influences the scope of the Digital Twin (Dimension 2) and determines the activities, information needs, and bottlenecks relevant to each stakeholder (dimension 1). Consequently, a DT use that is relevant and feasible in one typology may not be applicable in another.

To fully understand the impact of typologies on Digital Twins, the framework should be developed for the different typologies and compared against each other.

3 Conclusions

This report presents and discusses a conceptual Digital Twin uses framework for construction logistics, which explores the potential uses of Digital Twins within the specificities of the construction logistics context. This framework lays the groundwork for understanding the relationship between Digital Twins and construction logistics. By systematically categorizing the various dimensions of Digital Twins and logistics, it provides a structured approach to identifying viable Digital Twin applications that can enhance efficiency and ultimately contribute to the smarter, more sustainable management of construction logistics.

The conceptual framework also details some example potential application areas. These examples were detailed corresponding to four different Digital Twin scopes, municipality network, construction site, supply chain and bouwhubs. Different specific DT Uses were discussed for the different scopes. A network DT, for example, could offer municipalities a bird's-eye view 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, while bouwhub and supply chain DTs can streamline material management and optimize delivery routes, respectively. These application examples briefly demonstrate how Digital Twins can contribute to data-driven, efficient construction logistics practices for all the different stakeholders involved in the chain.

The conceptual framework now has to be detailed through its application to practical cases. This involves a thorough analysis of the specificities of construction logistics, such as detailed activities involved, responsible stakeholders, their technological landscape and process improvement requirements, and other organizational considerations concerning Digital Twins. The effect of different chain management typologies also has to be analysed. These analysis can set a scope through which relevant and feasible Digital Twin uses can be identified. The identified DT uses can then be verified by the stakeholders of the cases, after which a first version of the DT uses framework for construction logistics can be delivered.

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Appendix A

Framework design decisions

Stakeholder Requirements

To develop the conceptual framework, a requirement analysis was first done with experts from construction logistics to understand their needs and wishes. This was done using the framework meta-model represented in Figure 5. Broadly speaking, the meta-model represents that the framework is to be designed with a defined *scope and boundaries*, aiming to communicate *specific insights* to *users* who engage with the framework for a *particular purpose*. During the requirement analysis, these different elements were explored. ‘Breadth’ here is related to the context, ie., construction logistics, and ‘depth’ is related to Digital Twins. The derived stakeholder requirements for the framework are given in Table 3.

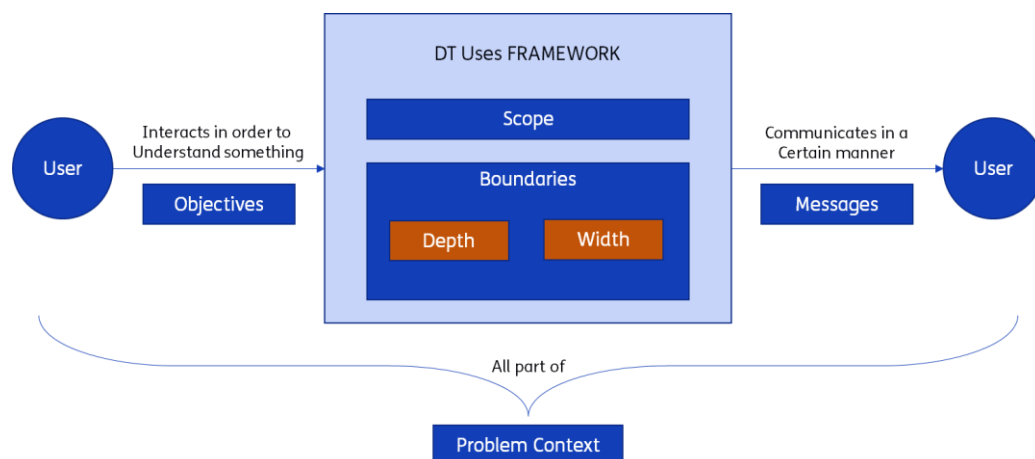


Figure 5: DT uses framework Meta model

Table 3: Stakeholder requirements

#	Stakeholder requirement	Type
1	The framework should provide an overview of the value Digital Twins can provide to construction logistics.	Objective
2	The framework should pinpoint specific application areas of Digital Twins in construction logistics.	Message
3	The framework should consider different types logistics coordination, vertical and horizontal	Breadth
4	The framework should consider different types of change management functionalities	Breadth
6	The framework should consider different logistics functionalities	Breadth
7	The framework should consider different logistics stakeholders	Breadth
8	The framework should consider different logistics activities	Breadth
9	The framework should reflect on the technological feasibility of Digital Twins	Depth
10	The framework should reflect on the sophistication level of the Digital Twin application areas	Depth
12	The framework should reflect on the scope and structure of Digital Twin of each application area	Depth

These requirements are intended to give a direction to the design of the conceptual framework. Note that these are not the requirements for the final framework, but just a starting list for the conceptual framework. When further detailing the framework, another set of requirements can/ will be derived from a broader audience.

Framework aspects

The first step in the design of the conceptual framework was to understand the various aspects of both Digital Twins 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 Digital Twins were deemed important, which includes (1) scope of Digital Twins, (2) Digital Twin applications (uses), (3) sophistication of Digital Twin use, and (4) feasibility of the Digital Twin use. For logistics, experts highlighted five critical aspects: (1) Logistics chain management typologies, (2) logistics functions, (3) logistics activities, and (4) chain players (stakeholders).

These Digital Twin aspects and Logistical aspects are discussed further below.

Digital Twins aspects

When exploring the implications of Digital Twins in the context of construction logistics, the questions are primarily in two directions: the value that Digital Twins bring to the different stakeholders, and how can it be realised. Breaking these questions down, there are four key aspects related to Digital Twins that are to be addressed, as illustrated in Figure 6. The right side of the flowchart are the aspects related to value, and the left side are aspects related to its realization.

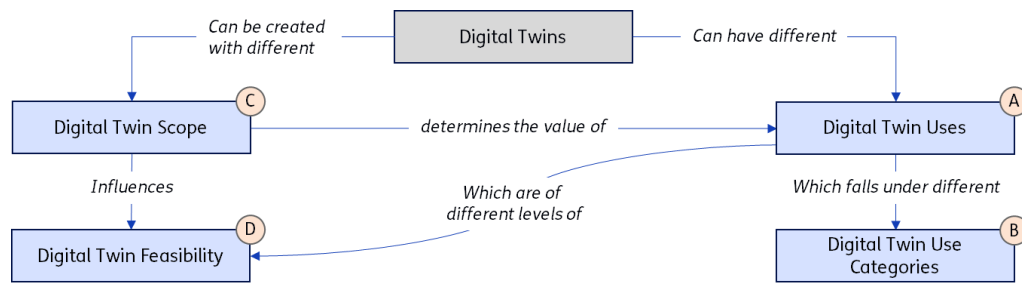


Figure 6: Framework aspects related to Digital Twins

Digital Twins are developed with a particular **scope** (see C in figure 6), which pertains to the 'physical system' aspect of the Digital Twin—essentially, which part of the real world is the Digital Twin replicating. It's important to recognize that Digital Twins can take different scopes 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 Digital Twins can add value to.

Within a defined scope, a Digital Twin can have various specific 'Digital Twin Uses', (see A in figure 6) which can be thought of as very specific application areas that the Digital Twin realizes within its scope. For instance, within the scope of a Digital Twin of a construction site, a particular "use" might involve a very targeted application, such as optimization of resource allocation in real-time.

These uses can be categorized using the different **Digital Twin Use Categories** (see B in figure 6) which is essentially the different levels of sophistication of a DT Use. While the potential applications of Digital Twins are vast, they generally align with one of five broad categories of sophistication, which have been identified through literature (see [4] for an overview): 1) historical analysis, (2) simulation/mimicking, (3) extraction/monitoring, (4) prediction, and (5) orchestration. These categories, illustrated in Figure 7, align with the intrinsic characteristics and functionalities of Digital Twins, such as data-driven insights, optimization through simulation, real-world sensing capabilities, predictive analytics, and the orchestration of complex systems. This categorization aids in understanding the 'type' of value the particular digital twin use is offering to the stakeholders.

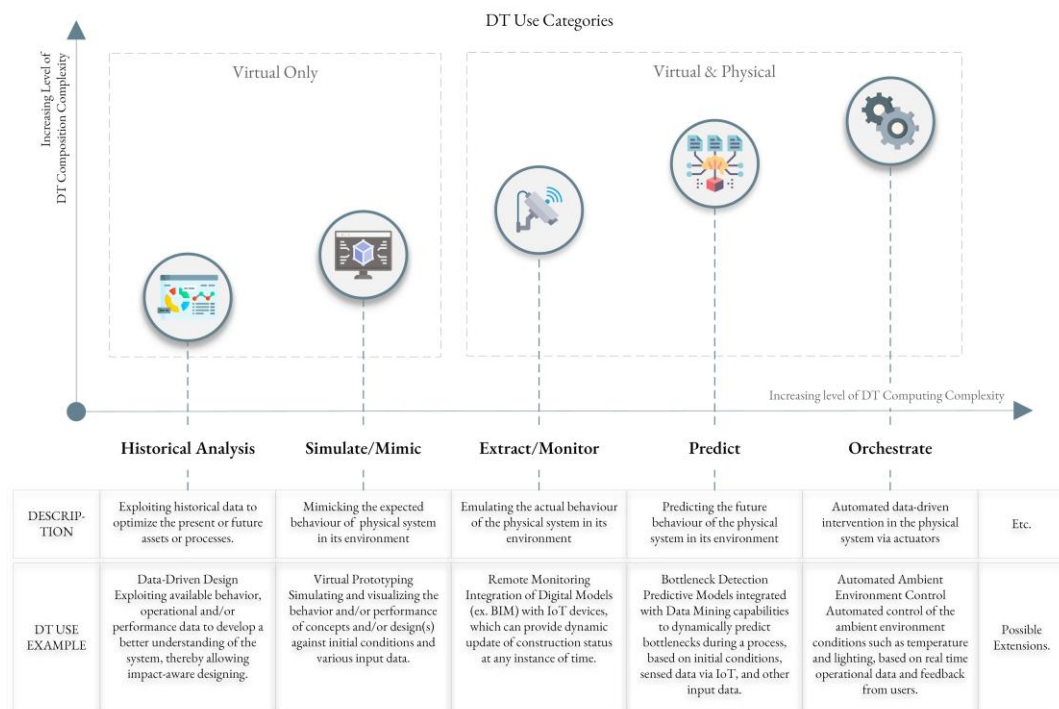


Figure 7: Digital Twin use sophistication levels

The scope of a Digital Twin significantly influences both its technical and operational **feasibility**. Moreover, the technological landscape and capabilities of the stakeholders involved in creating and utilizing the Digital Twin also play an important role in determining the practicability of its various uses. Feasibility of Digital Twins is an aspect with an intangible nature, which is however helpful for distinguishing between Digital Twin applications that are viable in the near term versus those that may be more realistic in the (far) future. 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.

Logistics aspects

Construction logistics involves a range of activities spanning the entire lifecycle of a construction project, from inception to completion. The various aspects related to it can be represented as shown in Figure 8.

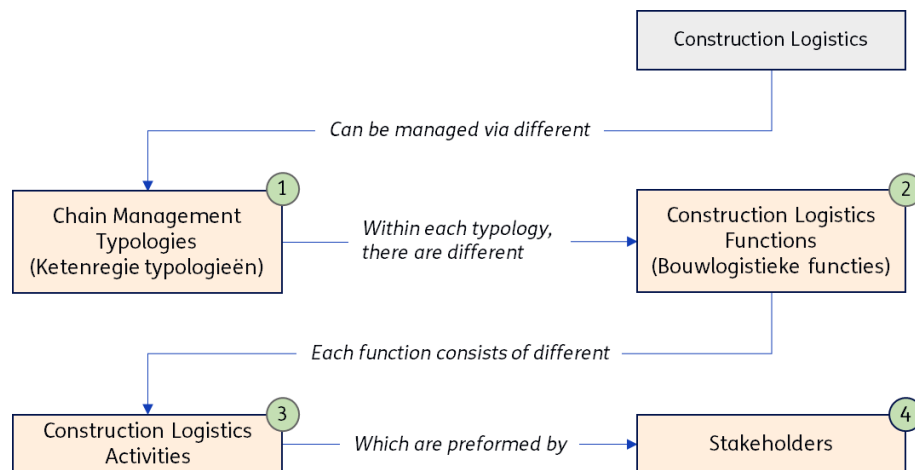


Figure 8: Framework aspects related to construction logistics

This complex ecosystem involves a variety of key stakeholders (see 4 in figure 8), each playing a pivotal role in the logistics chain, as detailed in Table 4. The stakeholders are key aspects to consider w.r.t Digital Twins because they are the developers, suppliers (for instance of data), and users of Digital Twins. This is not a complete list of stakeholders, but rather a starting point.

Table 4: Stakeholders in construction logistics chain [1]

#	Stakeholder
1	Supplier
2	Transporter (Logistics Service Provider)
3	Construction Site/ Main Contractor
4	Sub-Contractor
5	Municipality
6	Bouwhub (construction hub)

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 (see 3 in Figure 8) that are integral to ensuring this coordination. It can manifest in various **chain management typologies (see 1 in Figure 8)** [5]. These are essentially the organizational structures adopted to manage and facilitate these logistics operations. Some of these typologies require vertical coordination, while some requires horizontal coordination. The specific structure of a logistics chain, therefore, hinges on the chosen typologies, which are detailed in Table 5. Thus, from the perspective of Digital Twins, the typologies become key in terms of the scope and users of the Digital Twin.

Table 5: Different chain management typologies [5]

#	Chain management typology	Description
1	Reference model	No governance - current situation (reference)
2	Offset Model (Verrekening)	Offsetting of delivered transports – collaborative association of logistics service providers
3	Consensus Model (Consultation)	Cooperation structure with equal say for all partners
4	Concession Model	One logistics service provider (temporary, via concession) conducts the supply chain governance in an area
5	Government model (overheidsmodel)	Government conducts governance
6	Waterway	Supply chain governance on (waterway) road capacity/traffic management from the (waterway) road manager
7	Vertical - contractor	The governance lies with one party from the vertical chain (producer/supplier, logistics service provider, contractor)
8	Vertical - LSP	
9	Vertical - supplier	

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 insights gained from the TNO 4C Control Tower project, is presented in Table 6. It's important to note that this list is not exhaustive but an initial outline of key logistical functions (originally derived as functional requirements of the logistics control tower). These functions are some direct application areas for Digital Twins, and detailing what exact value Digital Twins can bring to these functions will be necessary.

Table 6: Logistics functions [1]

#	Logistics function	Description
1	Transport planning	Transport planning in construction flows to and from the construction project
2	Construction / production planning	Linking construction planning and transport planning (and production planning)
3	Asset planning (construction equipment)	Planning of availability / deployment of construction equipment (e.g., construction cranes)
4	Construction tickets (scheduling delivery time windows)	Planning of delivery times and construction tickets
5	Inventory space planning	Inventory management at construction site / construction hub
6	Consolidation of construction flows	Bundling / consolidation planning of transport streams (construction hub – construction site)
7	Day/ work package planning	Planning / compilation of (day/week) work packages based on construction activities
8	Tracking and tracing	Real-time tracking & tracing of construction logistics rides
9	Performance measurement/ monitoring	Performance measurement of construction logistics (KPIs: emissions, costs, load factor, productivity, ...)
10	(Road/ water) capacity management	Planning and allocation of the limited capacity of (road)ways to target groups

Logistics functions can be viewed as aggregations of numerous smaller, interrelated activities. Essentially, **logistics activities** constitute the logical sequence of operations in construction logistics at a project level.. It is also essential to identify which stakeholder is responsible for each activity. Such a list of activities might be different for different projects based on the adopted chain management typology. An initial overview of these activities (to communicate the intended level of detail) is provided in Table 7. Activities contribute to the exact use of Digital Twins, and the actual beneficiaries of the uses.

Table 7: Logistics activities (derived from [1])

#	Activity	Responsible stakeholder (possible)
1	Drafting bouwenvelop ¹	Municipality
2	Project proposal (tendering)	Construction contractor
3	Logistics plan for permits	Construction contractor
4	Realization plan	Construction contractor
	Logistics flow:	
1	Subcontractors inform main contractor	
2	Contractor makes tactical and operational plans	Construction contractor
3	Inventory location planning (in site)	Construction contractor
4	Material calls	Construction contractor
5	Material delivery- one to one delivery	Logistics service provider
5	Material delivery- bouw hubs coordinates	Bouw hub
6	Inner construction site logistics	Construction contractor
7	(Site) construction waste	Construction contractor

Framework Design

The various aspects of logistics and Digital Twins are intrinsically related and can be leveraged within a framework to thoroughly explore and articulate the value and feasibility of Digital Twins for construction logistics. An initial idea on how these aspects can be represented in a framework is shown in Figure 9.

The primary goal of the framework is to explore the potential value Digital Twins offer for logistics. This means that the **Digital Twin uses** becomes the central aspect of the Framework. These Digital Twin uses have to be categorized using various aspects to make it clear and concise. These different aspects within the framework will be termed as the different 'dimensions' of the framework.

Digital twin uses are very specific application area of Digital Twin, and as such it has to be linked to either logistics functions or activities to get a nuanced understanding on where exactly the particular use is adding value. Given that logistics functions are relatively broad, encompassing multiple activities and stakeholders, a more granular approach is essential for pinpointing the precise application areas of Digital Twins and understanding the specific value they deliver to each stakeholder. To achieve this, the framework adopts **construction logistic activity** to attach/ associate DT Uses to, as its first dimension.

¹ A "bouwenvelop" outlines agreements between a developer and a municipality on aspects like land price, construction plans, timelines, and legal terms.

The **scope** of the Digital Twin becomes the second dimension. Understanding the scope of discussion helps to identify the relevant stakeholders and their processes to which Digital Twins can add value to.

Based on the needs and challenges of stakeholders involved in each activity, Digital Twin uses can be identified for different activities. These Digital Twin uses can be further categorized using the different Digital Twin use categories, which helps in understanding the complexity of the Digital Twin use, or the type of value that particular use is providing. **DT use categories** (levels of sophistication) are thus the second dimensions along which DT uses can be categorized.

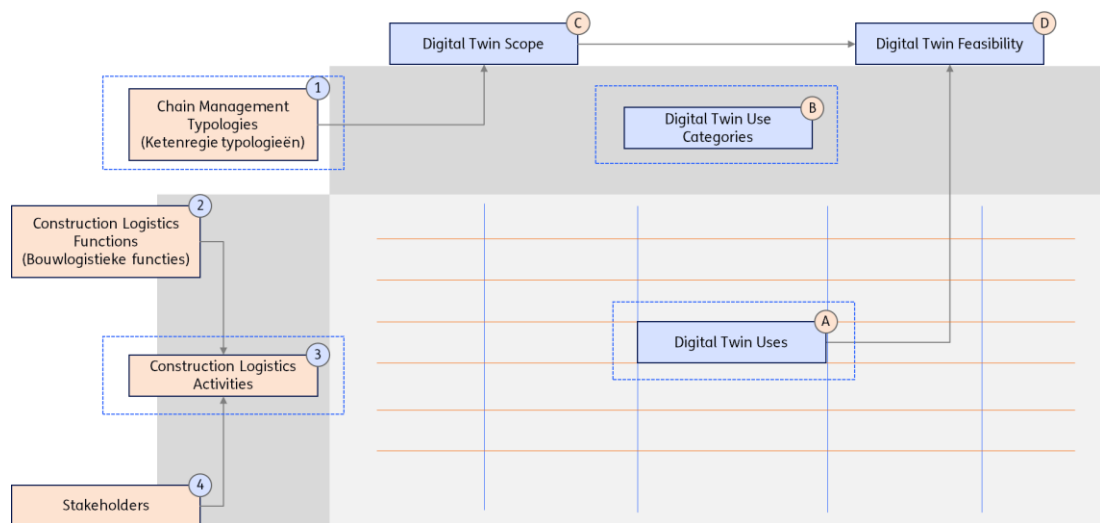


Figure 9: Design of DT uses conceptual framework - how different aspects related to Digital Twins from figure 3 and logistics from figure 4 are organized in one framework

The requirements and needs associated with various construction logistics activities are intrinsically linked to the chain management typology in place. For different typologies, the required information for different activities, the flow of this information (who provides what), and the process improvement needs could be different. Consequently, it's essential to incorporate **chain management typologies** as the fourth dimension in the framework.

At present, there is an absence of a direct one-to-one mapping between typologies and functions or activities within the logistics chain, in terms of what effect does different typologies have on the different functions/ activities. This means it might be necessary to create different DT uses frameworks for the different typologies if a comprehensive approach to incorporate all possible variations (in terms of how activities change or the different stakeholder needs for different typologies) within a singular framework cannot be realised. At the moment, such an 'all-in-one' framework is hard to envision. Once a clear mapping between typologies and logistics functions/activities is established, it will provide a more nuanced understanding of how different typologies influence the logistics process. This, in turn, will enable the framework to more accurately reflect the varied needs and requirements across different typologies and also will give the designer more insights into how to represent these different variations in one or many frameworks.

All the other important aspects will already be addressed within the chosen dimensions. Logistics functions and stakeholders are addressed through the construction logistic activities dimension. By breaking down logistics into specific activities, the framework naturally accounts for the functions involved and the stakeholders responsible for or affected by each activity. The scope of Digital Twins is closely linked to the chain management typology and the resultant activities, as the typology defines the operational context and scale at which Digital Twins are to be applied. The feasibility aspect is intrinsically related to both the scope of the Digital Twins and their specific uses, which, in turn, correlate with the construction logistic activities dimension. By analysing Digital Twin applications at the activity level, the framework naturally considers the technical and operational viability of these applications, taking into account the current capabilities and constraints within the construction logistics sector.

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