Strategic and operational construction logistics control tower

Harmelink, Rogier; van Merrienboer, Siem; Adriaanse, Arjen; van Hillegersberg, Jos; Topan, Engin; Vrijhoef, Ruben

DOI
10.1016/j.dibe.2025.100625

Publication date
2025

Document Version
Final published version

Published in
Developments in the Built Environment

Developments in the Built Environment 21 (2025) 100625

Contents lists available at ScienceDirect

Developments in the Built Environment

journal homepage: www.sciencedirect.com/journal/developments-in-the-built-environment

Strategic and operational construction logistics control tower

Rogier Harmelink [a,*], Siem van Merrienboer [b], Arjen Adriaanse [b,c], Jos van Hillegersberg [a,d], Engin Topan [a], Ruben Vrijhoef [e]

[a] IEBIS - BMS, University of Twente, Enschede, The Netherlands
[b] TNO, the Hague, The Netherlands
[c] MD - ET, University of Twente, Enschede, The Netherlands
[d] Jheronimus Academy of Data Science, 's-Hertogenbosch, The Netherlands
[e] MBE, Delft University of Technology, Delft, The Netherlands

ARTICLE INFO

Keywords:
Construction logistics
Construction management
Control tower
Construction logistics support

ABSTRACT

Construction companies have issues meeting building demands, and supply chain management promises are only sometimes fully utilized in practice. This paper investigates an IT artefact called the Construction Logistics Control Tower (CLCT). A CLCT is a control tower artefact specifically focusing on optimizing construction logistics activities across the supply chain. We distinguish four potential construction logistics application fields and, therefore, describe four potential variants of the CLCT. We design and narrow down these alternatives by applying a form of co-creation in which stakeholders design and set requirements for the artefact of interest. Our goal is to develop a reference architecture for the strategic and operational form in Enterprise Architecture. We focus on a transportation-based CLCT, which has a strategic component, *i.e.*, it predicts and manages long-term logistics activities regarding construction, and an operational one, *i.e.*, it operationalizes and executes daily transportation processes to support construction activities. Our work provides a core enterprise architecture diagram describing this CLCT variant's main functionalities. Next, we find that three key technologies need to be combined to realize such a system: Building Information Modelling, Geographic Information System and Transportation Management System. We discuss potential hurdles in the integration process and reflect on potential solutions. In the end, we envision that the construction of such a CLCT takes both a bottom-up and top-down approach but at least should be supported by a large consortium of stakeholders, constructing and supporting the system from their interests.

1. Introduction

The construction sector is facing a new set of challenges in solving the global and regional housing shortages. In Europe, specifically the Netherlands, additional problems make the situation even more complicated. First, a reduction in emissions in the whole process is needed, from the actual building to the construction logistics. Second, costs are rising due to global trade problems and stricter building regulations. Third, the construction sector seems to be rapidly adapting new building techniques (*e.g.*, prefabrication, modular construction, additive manufacturing, and robotics (Casini, 2022)) but has had issues for years with digitization for many reasons (*e.g.*, technologies, regulations and other aspects of digital transformation are in an early stage (Naji et al., 2024)). These challenges hinder the industry's ability to attain full efficiency and collaboration. Addressing these issues requires more active coordination and collaboration across the construction supply chain. In that sense, supply chain management and more active coordination and collaboration in the construction supply chain could be a potential solution (see Vrijhoef and Koskela (1999), O'Brien (1999)) to the earlier mentioned issues.

This paper approaches the problems discussed by applying a control tower artefact perspective. Different definitions and applications of a control tower exist (Harmelink, 2022). An early definition is given by Bleda et al. (2014), "A service control tower acts as a centralized hub that uses real-time data from a company's existing, integrated data management and transactional systems to integrate processes and tools across the end-to-end supply service chain and drives business outcomes". (Bleda et al., 2014), a more recent definition is given by Harmelink (2022): "An (inter-) organizational system which uses IT to optimize specifically (a part of) the service logistics supply chain". Control towers have the potential to integrate supply chain activities across different organizations. Waste reduction, higher efficiency,

* Corresponding author.
E-mail address: r.l.a.harmelink@utwente.nl (R. Harmelink).

https://doi.org/10.1016/j.dibe.2025.100625
Received 15 June 2024; Received in revised form 7 February 2025; Accepted 9 February 2025
Available online 19 February 2025

and better supply chain coordination should occur in the integration process. We use the definition of Harmelink (2022) as a basis.

We focus on a specific case of the control tower, called a Construction Logistics Control Tower (CLCT). A CLCT is a version of a control tower specifically focusing on construction logistics activities. Earlier research into practical applications of a CLCT was done in 2018 by TNO on sustainable construction logistics in inner cities (De Bes et al., 2018). Building on lessons learned in the research mentioned earlier, we investigate the CLCT in the case of Amsterdam. High-populated inner cities bring additional challenges for construction activities. The creation of zero-emission zones and limitations on construction transportation are additional restrictions in the already complex puzzle of inner-city logistics.

On the contrary, the construction industry's challenges provide an opportunity to innovate in multiple directions. New concepts like modular, circular, and sustainable construction, construction hubs, and IT developments (*e.g.*, Building Information Modelling, Geographic Information Systems, and the Internet of Things) can help tackle the issues presented. Also, multi-modal transportation options could reduce emissions by altering the mode of transportation (*e.g.*, via waterways). However, such solutions need coordination in the supply chains to succeed, which a CLCT could provide.

This paper aims to generalize and develop a reference architecture for a CLCT based on the Amsterdam municipality's case. We do this because the use case in Amsterdam is likely feasible for supply chain management practices to facilitate better construction logistics activities. Next, developing a CLCT will only occur if collaboration opportunities are researched and may catalyze further development. By developing a reference architecture in enterprise architecture, we implicitly generalize a CLCT's design, allowing other organizations to implement the solution in their socio-technical infrastructure.

We start in Section 2 by introducing the control tower concept and following with a more detailed perspective on the need for a CLCT in Amsterdam for construction logistics. Following this perspective, we introduce the methodology in Section 3, in which this research follows a co-creation approach in which stakeholders co-create the reference architecture. In Section 4, we develop a functional design of a CLCT (*i.e.*, an architecture which describes the inner workings) and discuss two versions of a CLCT. A strategic CLCT focusing on long-term logistics and an operational CLCT optimizing transportation processes. Section 5 describes technological opportunities, recommendations and limitations for the CLCT. We finalize the paper in Section 6 with a conclusion and discussion.

2. Academic and practical relevance

2.1. Literature review: The control tower concept

The control tower concept is new in the construction industry, but in the aviation industry, it plays a pivotal role in airplane takeoff and landing (Meekings and Briault, 2013). In the previous decade, the introduction of the term came from IT consultancy firms as a metaphor for an IT system that manages a part of the supply chain of business operations. The definition given by Bleda et al. (2014) is one of the core origins of the control tower concept in the IT domain.

However, the concept of a control tower still needs to be clarified. The commercial interest of IT firms has a potential conflict with the term to resell the old 'supply chain management software' concept under the term control tower. Conversely, control towers are running in different intra- and inter-organizational settings. This unclear division between intra- and inter-organizational applications begs the question of the exact boundaries of such an IT environment, an ongoing debate in the (academic) world).

In the academic literature, only Trzuskawska-Grzesińska (2017) synthesizes the academic literature on control tower research. For the rest, the literature discusses different applications and architectures of control towers for different purposes. Multiple examples exist which we mention, an integrated logistics control tower for off-shore (Mohammad and Mohd Azani, 2018), a rail-enabled control tower (Milenković et al., 2019), a transportation control tower (Baumgrass et al., 2014), and a service control tower (Topan et al., 2020).

As the previous section shows, each control tower operates in a specific niche, but this does not imply that control towers are standalone IT artefacts. Networks of control towers exist, which communicate and coordinate the supply chains as intended by their users. Such a combination of control towers is usually referred to in the literature as the cross chain collaboration center (4C) (see Dalmolen et al. (2015), Trzuskawska-Grzesińska (2017)). We refer to Harmelink (2022) for a more elaborate discussion of control tower applications, their architectures, and their definitions.

2.2. The need for a control tower for construction logistics support

The need for a CLCT is a double-edged sword. On the one hand, there is a need from a societal perspective to reduce particular waste and social nuisance (*e.g.*, emissions, traffic congestion, societal costs). On the other side, there is also an opportunity to digitize the supply chain in the construction industry. Oosterwijk (2017) discusses that fragmentation in the construction industry (*e.g.*, contractors, transporters, logistics service providers, producers and suppliers) and misalignment between production and information processes are reasons for inefficient supply chain organization. Building Information Modelling (BIM) could solve this, but BIM and logistic information are currently not well connected (Oosterwijk, 2017). Additionally, if logistic data is available, it is usually distributed over the individual organizations in the supply chain in different formats (Brusselaers et al., 2020), making it even more challenging to organize the construction logistics. A CLCT could be the first step in integrating the different data (formats) of actors in the construction logistics supply chain.

To further address potential issues, we also look at the challenges for (inner-city) construction logistics. These challenges are there, mainly due to the characteristics of construction logistics. Most construction sites receive deliveries early during the workweek (before 09:00), of which some goods need to be handled by a crane, lengthening the delivery process (Sezer and Fredriksson, 2021). New production processes (*e.g.*, prefabrication and modular approaches) further complicate the logistical process. If the construction site uses modular construction, which is becoming more popular, on-time delivery of the individual modules is necessary for the construction planning. However, the construction industry has uncertainties surrounding the construction supply chain (Peiris et al., 2023), making modular construction difficult. In inner cities, these construction logistics require no or low emissions due to legislation; this is possible but requires good planning and collaboration between stakeholders (Venås et al., 2020). The concept of construction logistics hubs could reduce the burden on inner cities by offering logistics capacity for multi-modal transportation and realizing modular construction. However, these are challenging to realize due to different drivers that motivate end-users and implementers in practice (Janné and Fredriksson, 2022).

The core issue lies in supply chain integration in the construction (logistics) industry. Although benefits are envisioned (*e.g.*, reducing costs, removing waste, gaining a competitive advantage, creating value, improving planning, etc.), and research into supply chain management in the construction industry has shown these benefits, problems in the actual supply chains still exist widely (Papadopoulos et al., 2016). If a CLCT is going to be applied, some form of supply chain integration would need to occur. However, the construction industry usually has many Small and Medium Enterprises (SMEs) with more significant scepticism towards supply chain management practices (Dainty et al., 2001). The considerable fragmentation of parties in the construction supply chain even limits the levels of integration achievable (Briscoe and Dainty, 2005). Therefore, such parties need to be included, not only by mere stakeholder management but by showing the practical (economic) benefits of CLCT solutions.

Many studies have investigated the potential benefits of supply chain management in the construction industry. Especially on transportation, probable benefits are enormous, as 39 to 58 percent of total logistics costs are transporting goods (Ying et al., 2018). In their project, TNO has shown these benefits in practice, with a 50 to 65 percent transport reduction in the finishing phase and 80 percent in the shell phase (De Bes et al., 2018). Additional savings on the side of better management of supply chain-wide construction logistics will also result in better on-site logistics performance (Sundquist et al., 2018).

The artefact of a CLCT could be a tool and a facilitator for better cooperation in the supply chain management process in the construction (logistics) industry. Other applications of a supply chain control tower show that integration requires a combination of technology types (*i.e.*, long-linked, mediating and intensive[1]) to realize an intelligent supply chain (Vlachos, 2023). However, control tower applications also need a reasonable organizational readiness, technology requirement and supply chain maturity (Vlachos, 2023). In the construction industry, this might be problematic due to a lack of business case, absent governance model, improper use of ICT across the chain and (perceived) risks in data sharing (Staring, 2019). On the contrary, the CLCT could be an open platform, facilitating necessary information for all stakeholders involved in construction projects and providing public services and residents in construction areas (Tesselaar, 2020). The CLCT could even be part of a trust-building strategy (Meissner, 2015).

As a preliminary for this research, we investigated the motivation of stakeholders related to the case of inner-city construction logistics in Amsterdam. The consortium comprises various stakeholders, from the municipality to construction (logistics) companies and an IT provider. The group expects that insights into their current supply chain will result in gains in efficiency and cost savings, especially in transportation processes. However, if asked how to approach the construction of a CLCT, conflicting opinions are given (*i.e.*, top-down versus bottom-up). The consortium, however, also recognizes potential risks regarding a too broad application on the supply chain, limited support and lacking digitization (van Merriënboer et al., 2023). There is a need for a CLCT, but the risks surrounding its application might limit its realization.

3. Methodology

The risks presented in the previous section are also an opportunity. We bridge the potential risks by drafting a reference architecture for a CLCT. We do this with the help of enterprise architecture. Enterprise architecture is "a conceptual framework that describes how an enterprise is constructed by defining its primary components and the relationships among these components" (Rood, 1994). Compared to an information system architecture, enterprise architecture takes a broader point of view by including the dependencies with business processes, technologies and organizational structure. We use enterprise architecture, standard terminology for development, integration and communication about (information) system standards (Rood, 1994).

Developing an enterprise architecture is comparable to developing an information systems artefact. Therefore, we use the engineering cycle for information systems and software engineering as a basis (Wieringa, 2014). This engineering cycle is a more generic Design Science Research methodology specialization. It focuses on creating an artefact which should be validated (*i.e.*, checked on valid assumptions in a theoretical setting) and evaluated (*i.e.*, implemented and analysed in practice). The engineering cycle consists of the phases: problem investigation, treatment design, treatment validation, treatment implementation and implementation evaluation (Wieringa, 2014). For this study, we limit ourselves to developing the CLCT from problem investigation until and including treatment validation. We later link these engineering cycle steps to our primary methodology in this section. Conversely, we need to specify how to develop the enterprise architecture itself.

Developing an enterprise architecture can be done in multiple ways. Kotusev (2016) outlines three approaches to enterprise architecture development: the traditional, the MIT and the DYA approach. The TOGAF[2] fits within the traditional approach spectrum, in which step-by-step enterprise architecture development occurs. The traditional approach is easy to understand and highly centralized, ideal for small and stable organizations (Kotusev, 2016).

On the contrary, the traditional approach also neglects that "the enterprise is not an ordinary system like a machine or a building and cannot be architected or engineered as such" (Bloomberg, 2014). Löhe and Legner (2014) see additional issues with the traditional approach, especially regarding the cumbersome documentation required and low utilization thereof. Also, the step-wise approach offers a clear structure but provides less flexibility for larger, decentralized and more volatile organizations (Löhe and Legner, 2014).

This research focuses on developing a CLCT reference architecture for a broad consortium of companies and organizations; therefore, the consortium is highly decentralized. The traditional method is unsuitable, but there still is a choice between the MIT and DYA approaches; the MIT approach by Ross et al. (2006) sees enterprise architecture as a basis for business strategy development and focuses on a so-called core diagram for long-term enterprise architecture. The DYA approach, on the other hand, is more pragmatic and only develops enterprise architecture documentation at the right time. The MIT approach suits large and complex organizations with stable business models. In contrast, the DYA approach is more for organizations operating in unpredictable and dynamic environments (Ross et al., 2006), in which organizations still need a fully-fledged business model. We opt for the MIT approach in this research because it focuses on a core diagram. For the DYA approach, a clear business case should be present, which is lacking in the case of the CLCT.

The MIT approach has three steps: (1) Decide on the operation model, (2) Develop the Core Diagram, and (3) Establish the IT Engagement Model. For this research, the focus is on the first two steps, as implementation is, in the case of the CLCT, a long-term project requiring the commitment of stakeholders; the engagement model is out of scope, as it coordinates the alignment of IT and business objectives resulting from the enterprise architecture model. We combine the MIT approach with a co-creation designing approach.

Co-creation is an evolving paradigm which has developed from the idea of the willingness of customers to participate in the design and creation of products and services (Prahalad and Ramaswamy, 2000). As a result, co-creation can also increase the possibility of adopting certain products, which could benefit the CLCT artefact in general. However, multiple definitions of co-creation exist, and we use the following: Ramaswamy and Ozcan (2018) define co-creation as "enactment of interactional creation across interactive system-environments (afforded by interactive platforms), entailing agencing engagements and structuring organizations." (Ramaswamy and Ozcan, 2018). In this research, we co-create with the stakeholders involved from the consortium, and we align the co-creation paradigm with the MIT approach for enterprise architecture. The following table describes our substeps and approaches within the MIT approach.

Table 1 shows the seven steps we took to develop the reference architecture for the CLCT, also related to the engineering cycle. We narrow down four conceptual CLCT alternatives to a single reference architecture. All consortium members (*i.e.*, municipality, construction

[1] See Thompson (2017) and Appelbaum (1997) for the technology typology

[2] The Open Group Architecture Framework (TOGAF) is the most well-known and extensively described methodology. TOGAF is a broadly adopted standard in industry.

Table 1
Steps taken in the development of a CLCT reference architecture.

MIT Approach Step	Goal MIT Approach	Co-creation steps taken in this research
1. Create an operating model.	Choose processes and IT systems to be integrated and standardized.	(1) Investigate and discuss potential construction logistic processes to be integrated and standardized. (Problem investigation) (2) Conceptualize four potential CLCT solutions based on first consortium discussion. (Treatment design) (3) Stakeholders vote on the two favourite CLCTs to further develop, resulting in two CLCTs to develop. (Treatment validation)
2. Develop enterprise architecture.	Develop an enterprise architecture as a strategic long-term architectural vision, which links systems, processes and technologies.	(4) Co-creation workshops, participants are asked to sketch their designs in mock-up style which are the basis for discussion. (Problem investigation) (5) Transferring the designs of the workshops into CLCT prototypes. (Treatment design) (6) Individual semi-structured interviews with stakeholders to co-create core CLCT functionality. (Treatment design) (7) Develop core enterprise architecture reference model and validate with expert feedback (Treatment validation)
3. Establish the IT engagement model.	Ensure the realization of the enterprise architecture by providing alignment between IT and business objectives based on governance mechanisms.	None

Table 2
Participants in the interviews and workshops.

Type of organization	Function	Experience	Background
IT company	Director	23 years	Civil Engineering, Business Administration
Construction company	Project leader	15 years	Civil Engineering
Municipality	Policy officer	31 years	Landscape Architect
Entrepreneurial organization	Knowledge expert	26 years	Applied Economics
Construction company	Project controller	3 years	Industrial Engineering
Transportation company	Company owner	24 years	Logistics & Economy
Construction company	Project manager	16 years	Civil Engineering
Construction company	Manager	8 years	Civil Engineering
Construction company	Advisor sustainability	27 years	Construction Management
Construction company	Teamlead construction logistics	9 years	Construction Management

(logistics) organizations, transportation companies and business organizations) provide input and co-develop the reference architecture by discussing and interacting. In Table 2, we show the ten participants and interviewees in the different workshops and individual interviews. The participants are from different types of organizations, functions and years of experience. However, they all have experience in the construction (logistics) industry, and a few participants even have far-fetched experience with BIM and other techniques within the construction sector. We design the artefact of interest, namely, the CLCT. However, we do this in multiple steps.

4. Development of a reference architecture for a CLCT

In this section, we design the artefact, the CLCT. We do this for two variants, a strategic and an operational version, which we will explain later. First, we describe the underlying case in Section 4.1., fuelling the enterprise architecture design, which is infrastructure works taking place in the Wallenarea, the historic centre of Amsterdam, in the Netherlands. Second, we conceptualize multiple variants in Section 4.2 of a CLCT with different perspectives, describe them, and narrow them down to two potential solutions. Third, we ask consortium members to sketch and visualize the CLCTs of interest discussed during multiple workshops. Fourth, we transform early sketches into a CLCT prototype, described in Section 4.3 as the basis for individual interviews. Based on these interviews, we designed an enterprise architecture core model for a CLCT in two versions: a strategic CLCT and an operational CLCT, discussed in Sections 4.4 and 4.5.

4.1. The Amsterdam case: The Wallen area

For this research, we looked at the case of Amsterdam. Amsterdam has a unique history with its inner city, primarily because of the combination of densely populated streets combined with waterways. The Wallen area is hard to reach by road; therefore, the municipality stimulates the use of waterways for logistical purposes. Historically, the waterways were a means of transporting goods to and from the warehouses near the water. Now and in the future, the municipality would like to see the use of these waterways increase to relieve the pressure on the busy roads and quays and to improve the living environment and accessibility of the area.

In 2020, the City of Amsterdam established the long-term Programme for Bridges and Quay Walls (PBK) to restore 800 out of 1,800 bridges and 200 out of 600 kilometres of quay walls throughout the city. These objects are in critical shape, and in 2020, a quay wall even collapsed completely. The first projects of the PBK program started in 2023 and 2024, particularly in the historic city centre. Besides the PBK program, the city runs a parallel maintenance program to renovate inner-city streets.

In the case study, we looked into the logistics of three concurrent nearby projects: two quay wall renovations and one street renovation. The case study aims to investigate and assess the potential for combined logistics and transport aimed at transport movement reductions. The first case study was a past case and looked into transport registrations from a hindside after the completion of three concurrent projects. The second case study was a live case based on project planning and bills of materials of three other projects before they started. The quest in both case studies was to find logistics optimization when the logistics of the three projects were combined rather than kept separate. The case study research by TU Delft showed that the potential savings in the past case could be some 1.000 ton-kilometres (7% of all transports added up) if only transport combinations and usage of a construction hub could be applied.

If we optimize project planning and activities with the help of a CLCT, *i.e.* adjusting the timing of project activities and transport movements, we save an additional 1.135 ton-kilometres (7%). In the past case, 14% of potential savings on transport activities could be possible. The savings added up to all 339 truck movements in the live case. Because of the modal shift of trucks into ships, 57 ship movements (equalling some 230 trucks) are necessary, adding to the existing 52 ship movements (210 trucks). The total savings of the live case would be 20%. More details on validating this use case are visible in Vrijhoef and Harmelink (2024). The question is, where should the CLCT focus on achieving these savings (van Merriënboer et al., 2023).

4.2. Potential CLCT solutions and narrowing down the alternatives

Based on the use case described earlier and preliminary interviews with consortium members, we envision four potential CLCT solutions: the transportation CLCT, the material planning CLCT, the logistics space CLCT, and a waterway CLCT. Each CLCT type has a unique focus and different functional requirements. Therefore, we need to recognize the CLCT type with the most potential in daily operations for the stakeholders involved.

Table 3 summarizes the different types, their needed functionality and data availability. We ask consortium members to vote for two of their favourites regarding practical contribution to their business processes and realizability. The consortium members preferred the transportation and logistics space CLCT options to investigate further. Table 4 shows the first and second preferences per organization. Please note that we have focused on the preferences of companies involved in the supply chain; we have explicitly excluded entrepreneurial organizations and an IT developer from voting that they are not end-users in the CLCT environment.

4.3. Co-creation workshops

For both CLCT types, we organized two workshops where co-creation is crucial. We asked participants to prepare for these workshops with a mock-up or sketch of what, in their opinion, a CLCT solution is for the type of interest. Additionally, participants reflected on two topics. First, we asked them about the potential problems that the CLCT could help solve. Second, we asked the participants to determine the need for specific information in such a system and its availability.

4.3.1. The transportation CLCT

The problem of collaborative transportation

For the transportation CLCT, the consortium acknowledges that the current ways of working are highly individualistic, *i.e.*, there needs to be collaboration regarding the transportation process. There is contact with the supplier for typical transportation over the road, and a transporter does the transportation activity. Construction companies usually have a fixed long-term agreement with a specific water transporter if something needs transport via a waterway. This agreement could potentially hinder collaboration between transport companies.

On the other hand, new concepts also provide opportunities. The consortium mentions that circularity could be an opportunity to fill the empty spaces in transport by transferring waste for reuse in other construction projects (*e.g.*, application of industrial symbiosis), which was also researched and validated in the Amsterdam cases. The municipality recognizes that it should have an overview of the transportation activities for traffic management purposes. However, parties should also receive incentives to approach transportation for construction logistics collaboratively.

The need for information

A transportation CLCT should connect to different information sources and databases. A link should exist with transport management systems, traffic management systems, accessibility, and environmental data from the municipality and systems hosting construction and materials planning. There should also be a certain level of information depth in these systems. Experts involved in the research gave examples of detailed information that needs to be known, including transports at a particular moment and what they are transporting. As the Amsterdam case shows, the CLCT should be an intelligent system that identifies collaboration opportunities and predicts future transportation movements and congestion.

A first concept of a transportation CLCT

Based on interviews with practitioners involved in the research, two practical applications for the transportation CLCT are feasible. One is a strategic version, which can predict and anticipate future construction logistics activities. The second is an operational version, which facilitates the ongoing transport process in the short term but also helps to predict and anticipate short-term changes. Conceptually, the strategic version facilitates long-term anticipation of transport through the urban environment, and the operational version helps improve logistics coordination and collaboration in and between projects in urban areas in the short term.

4.3.2. The logistics space CLCT

The problem of sharing logistics space

In the case of the logistics space CLCT, participants in the workshop mentioned that working with limited space for storage (*e.g.*, for stock, temporarily storing building materials and construction machinery) is integral to their daily operations. The participants mentioned that while working in public spaces, there are agreements with the municipality and other parties on where construction equipment and materials can be stored. Managing the limited space on construction lots is vital to keep operations ongoing. Adding construction hubs or extra temporary local storage close to projects is a valuable solution to increase logistics efficiency.

However, some issues are specific to particular projects. In the case of Amsterdam, there is limited or no space on the quay wall itself or nearby. If there is space, there are often zero emission restrictions,

Table 3
Description of CLCT types.

CLCT Type	Description/Main focus of the CLCT	Needed functional requirements	Data availability	# votes
Transportation	The focus is on sharing transportation resources, therefore reducing waste and empty transport activities	A link with transport management systems A link with construction planning systems	There is a six-week planning with delivery times, but additional data is hard to get or not digitized.	10
Material planning	Looking for opportunities to collaborate on the sourcing of materials for construction projects.	A link with construction planning systems A link with material planning systems	Construction planning is usually available for individual organizations but not often combined over multiple projects.	2
Logistics space	Optimizing the availability of space and inventory in construction hubs and sites	Planning inventory and space available	Construction hubs have insights into the usage of their spaces. However, on construction sites this might be more cumbersome.	9
Waterway management	Managing traffic and capacity on the waterways	A link with transport planning systems A link with traffic management A link with AIS data	AIS data is available relatively easily. Information on routing and traffic intensity is available as well.	1

Table 4
First and second choices for CLCT types by companies.

	Transportation	Material planning	Logistics space	Waterway management
Construction company	2	1		
Construction company	1	2		
Construction company	1	2		
Construction company	1	2		
Municipality	1		2	
Construction company	1	2		
Construction company	1	2		
Construction company	1		2	
Construction company	2	1		
Transportation company	2	1		
Dredging company		2		1

requiring charging facilities for electrical equipment. Maintenance activities for quay walls often have storage facilities in hopper barges on the water. The Amsterdam case study shows the advantages of sharing logistical space and transport between two or more projects. This sharing requires additional agreements among the contractors and the municipality, as well as nautical firms and residents using the waterway.

The need for information

The main problem is retrieving timely and adequate information on logistics space available in inner cities. Additionally, the construction companies mention that they would like to know which locations are available for usage as temporary storage facilities. They would like to see which logistic spaces on land and water are available and with which certainty they can use them. Additionally, construction hubs could offer their logistic space and services within the CLCT environment. For zero-emission equipment, the CLCT should provide information on recharging locations. On strategic locations close to projects in the city centre, the construction hubs and municipality could deliver constant supplies of materials and move out waste in efficient transport loads for concurrent projects, which will then be able to collect materials in and waste out flexibly at those locations, and preferably by water transports.

A first concept of a logistics space CLCT

The participants' first sketches are in a platform where the information mentioned earlier is available. The CLCT has more of a platform function that provides information about selected parameters, such as transports and loads planned and space available, than already envisioning and deciding on particular supply chain organization and logistics optimization. If optimization is possible within this type of CLCT environment, it could support communication among firms about the actual state of limited space available in specific locations given a set of materials, equipment, etc.

4.3.3. Selecting a definitive type CLCT concept

During the multiple organized workshops, there was some hesitation regarding the feasibility of one of the two concepts: the logistics space CLCT. According to multiple participants, the information that should feed into a logistics space CLCT lacks, such as external projects and events consuming public places and traffic situations. Digital information retrieval technology could fill that gap, which requires investments but could be rather costly. So, based on these expert opinions, we decided to investigate the transportation CLCT further over the logistics space CLCT. This choice is mainly due to the limited information and a lack of business cases. As stated earlier, we know that supply chain partners can benefit from the transportation of CLCT. For a logistics space CLCT, more research should occur into the business and technical feasibility.

We distinguish two types of transportation-focused CLCTs: strategic and operational. The former focuses on long-term decision-making and predicting, while the latter prioritizes daily operations. We interviewed consortium members individually and showed them a prototype of the strategic and operational CLCT versions. Based on this prototype, we applied a semi-structured interviewing technique to retrieve potential requirements and needs for the CLCT of interest. These interview results are analysed and clustered. We generalize similar functionality requirements to those of a specific application within the CLCT. In Tables 5 and 6, we present different application components (*i.e.*, modules) for which individual stakeholders have mentioned interest in their functionality in the interviews, where the different letters represent the stakeholders. To conclude, we validate the functionalities applicable to the Amsterdam case study with the help of the municipality and firms involved.

Tables 5 and 6 show the functional modules and stakeholders involved, respectively. We link the different stakeholder functional requirements to generalized functional modules. We develop these generalized modules based on the commonality between functional requirements. For example, if functional requirements deem certain

Table 5
Types of CLCT modules and stakeholder interests.

Type of CLCT module	A	B	C	D	E	F	G	H	I	J
Strategic CLCT										
Municipality Construction and Safety Information	■		■	■			■	■	■	■
Circular Hub							■	■		
Traffic Management			■							■
Construction Management		■	■	■	■		■	■	■	■
Construction Logistics	■	■	■	■	■		■	■	■	■
Operational CLCT										
Transportation Intelligence	■	■	■	■	■	■	■	■	■	■
Construction Planning	■	■		■	■		■	■	■	
Transportation Insights	■	■	■	■	■	■	■	■	■	■
Water Transportation		■		■	■		■	■	■	■
Interfaces	■	■	■		■	■	■	■	■	■

Table 6
Different stakeholders were involved in the interviews.

Letters	Type of company
A	IT company
B, E, G, H & I	Construction company (E = specialized in water on construction)
C & J	Municipality
D	Entrepreneurial organization
F	Transportation company

circularity features, we create a module. The tables explicitly show the link between the modules and the stakeholder requirements. These modules form the basis of the strategic transportation-focused CLCT and the operational transportation-focused CLCT, which we discuss in-depth in the following sections.

We follow a generic structure to describe the strategic and operational CLCT. First, we describe the supported business processes, which are why a CLCT should operate and positively impact outcomes. Then, we describe a generic CLCT structure, showing the main application modules in the type of CLCT. Following this, we investigate the functionality of the modules and validate the modules based on the Amsterdam case. Finally, we reflect on the supporting technologies needed to realize the CLCT in the bigger picture. Some of these technologies are key, which we will discuss in the second to last section.

4.4. Strategic construction logistics control tower

The strategic CLCT focuses on long-term (*i.e.*, a time horizon of at least a few months, expanding to multiple years) transportation in the construction logistics supply chain. However, based on the functionality needs and requirements described by individual stakeholders, the strategic CLCT's application is broader. Firstly, we discuss the business functions the strategic CLCT supports and show how the CLCT aligns with these business functions and their processes. Secondly, we show the technologies required to get the strategic CLCT running. Finally, we describe a more in-depth strategic CLCT design and its functionality, for which we highlight specific modules.

4.4.1. The supported business processes

Fig. 1 shows the strategic control tower and its technologies support two main business processes.[3] The first is the construction coordination and communication function. Usually, a municipality is responsible for keeping a city accessible and functioning according to regular standards. However, they depend on how other stakeholders in the construction landscape (*i.e.*, construction companies, transporters, and citizens) cooperate with them. The strategic CLCT should support the municipality mainly in keeping the city accessible and managing traffic so that hindrances are kept to a minimum while informing stakeholders of potential hindrances and achieving ambitions on a city level, such as sustainable and multimodal transport. Next, it should provide the municipality with the information necessary to coordinate the whole process.

On the other side of the business processes, we see a more for-profit-oriented business function regarding construction logistics and management. Construction companies are especially interested in realizing and executing construction processes (*i.e.*, building and maintaining). However, customers that the construction companies serve trigger these processes. A few critical business processes that the strategic CLCT supports are managing construction activities, realizing construction logistics, maintaining built assets and, for some organizations, constructing buildings with circular resources.

These two business processes get support from five modules, *i.e.*, the traffic management module and the municipality construction and safety information module, which mainly support the construction coordination and communication business activities. The other three modules are construction management, construction logistics and the circular hub module. These three mainly support the construction logistics & management functionality. We discuss the functionality of the individual modules in more depth in the following section.

4.4.2. Core functionality

At the heart of the functional design in Fig. 2 is a digital twin simulation in the Construction Management module. This digital twin simulates the construction environment, can forecast building activities with, for example, BIM data, and can predict logistics activities needed in the future. Based on this, the construction logistics module could plan, predict and check the realization of logistical flows and their restrictions. Predicting these logistical flows is critical, as in inner cities, additional restrictions like zero-emission zones and limitations to using specific resources create additional barriers for construction companies. The construction management and construction logistics module closely interact with the traffic management module, which forecasts long-term traffic and potential traffic congestion.

The basis for the digital twin, traffic management and construction logistics module, lies in the Municipality Construction and Safety Information module; construction companies are often legally required to request a permit for construction activities in inner cities. Extracting this information from the local systems (*e.g.*, from VICTOR in the Amsterdam case) could generate additional information for future construction activities. These feed into all the other modules in the strategic CLCT. An essential component in the system is the circular hub module/interface; this one connects with information platforms that run circular (construction hubs), as described by Yu et al. (2023). The CLCT could recognize potential circular resources companies use

[3] Shown in the upper yellow business layer of the figure

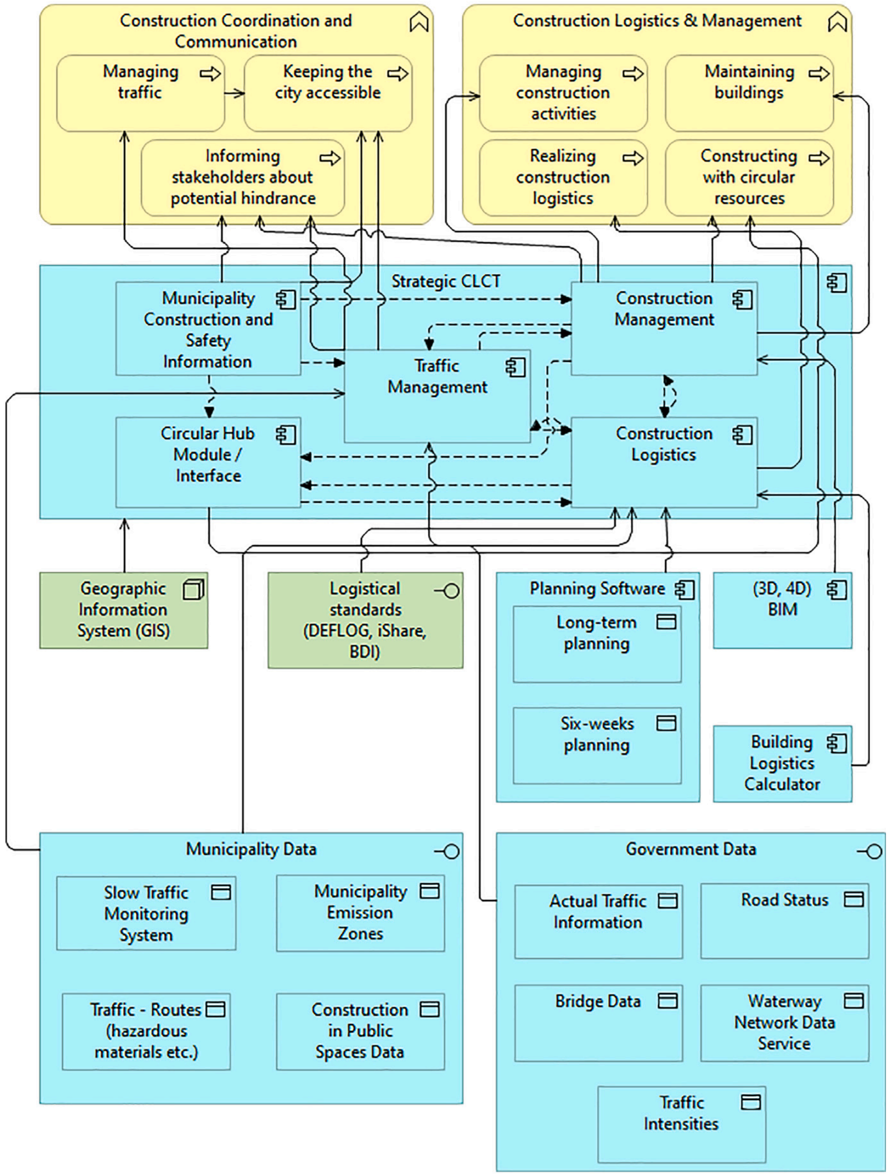

Fig. 1. Strategic CLCT and its technologies.

for building and feed them into other applications, *i.e.*, the construction management and logistics modules.

We have validated these designs in the Amsterdam Case setting. The following modules mainly support construction coordination and communication business functions, *i.e.*, municipality construction and safety information and traffic management modules. The data from permit applications (*i.e.*, VICTOR and BLVC data for Amsterdam) are mostly insufficient, unstructured, and not known on time for strategic logistics planning. However, the departments for 'city direction' and 'works programming' look ahead a few years in advance, and this data could be helpful. For the traffic management module, the usefulness of Amsterdam's traffic models and automated accessibility assessment modules based on vehicle weight, size, and emissions are significant. There is a need to develop such automated models and modules for nautical transport, too.

The other modules, mainly supporting construction logistics and management business functions, have also been validated. For bridges and quay walls in Amsterdam, predicting status, maintenance, and projects takes place in a structured process funnelling in from 5–10 years of look ahead planning for urban areas to 2–4 years of technical preparation for concurrent projects in areas, and 0–2 years project preparation of individual projects. Logistics and traffic usually cover these three phases, from strategic to tactical to operational levels. This division between phases and levels could be helpful in the construction management module. For construction logistics, we identified and used potential opportunities and efficiency improvements for the Amsterdam case via an integrated logistics approach to concurrent projects. The effect was that bundling and optimizing transport movements would considerably reduce the total amount of transport movements and obliterate all land transport, adding efficient water transport instead (see Vrijhoef and Harmelink (2024)).

In the final module, the circular hub module, we see that in Amsterdam, circular reuse directly on and between concurrent projects in the city centre is possible, and logistics improvement, *i.e.* transport movement reductions, are calculated as a result. This reuse between projects would require additional micro hubs or temporary storage space for reusable materials in the proximity of concurrent projects, either on land or on water in barges.

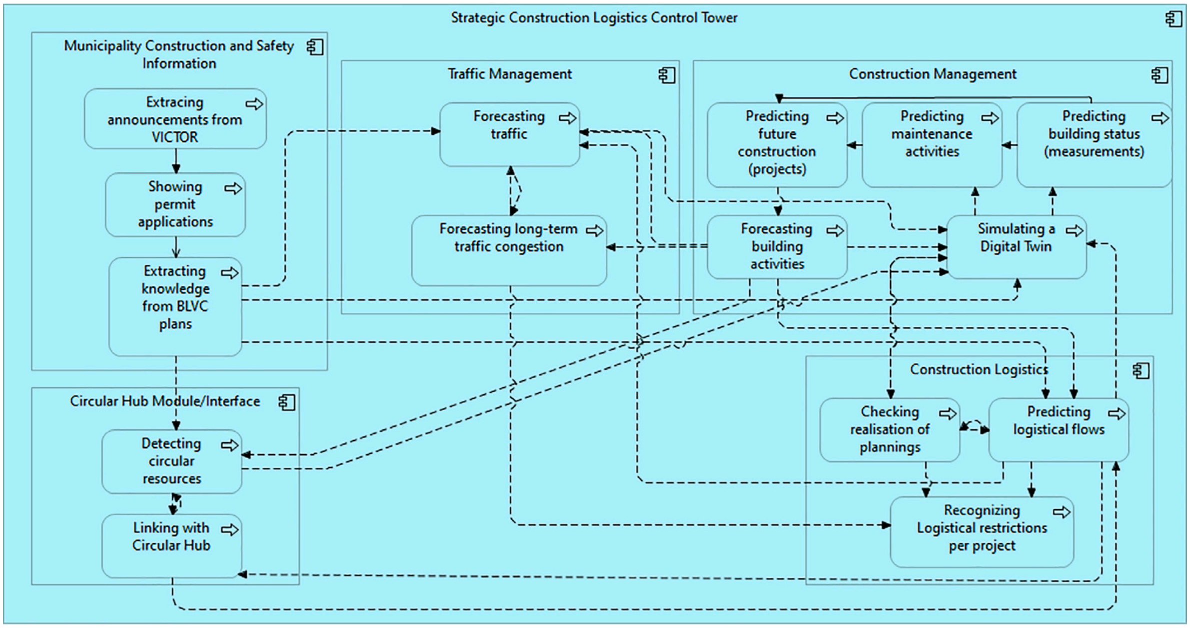

Fig. 2. Strategic CLCT application and their inner workings.

4.4.3. The supporting technologies

A strategic CLCT needs support from (external) technologies. We model technologies as external applications, standards or nodes attached to the CLCT artefact. Fig. 1 shows the different technologies linked to the strategic CLCT application. We recognize six identifiable technologies that are important, especially for the strategic CLCT. Logistical standards are an absolute necessity for the construction logistics module. As companies have different data store standards, linking at least well-adopted logistics data-sharing standards to the (strategic) CLCT would be wise. Examples of such standards in the Dutch logistics sector are DEFLOG, iShare and BDI.[4]

Building Information Management (BIM) software should also link to the construction management module. The digital twin, which plays an essential role in managing construction activities, should be modelled according to 4D BIM standards such that buildings are viewable in 3D, but also making life more manageable from a planning perspective and potential changes that are the basis for simulation in the digital twin. To complete the addition of 4D BIM, Geographic Information Systems (GIS) should be linked to the (4D) BIM data to add a geographical perspective, such that the CLCT could easily switch, on a map, between different digital twins, which should be according to BIM standards. In validating the Amsterdam case, using widely used basic applications, such as MS Excel, and the potential for semi-automative logistics of the input and output data in such software are discussed based on OTM standards.

A link with planning software is necessary because we focus on long-term construction activities in the strategic CLCT. This link must be there to check the digital twin simulations on one side and the other; also, the (realized) plans must be checked and linked to other activities. However, in the case validation of the Amsterdam case, the question was asked to what extent the data would be adequate due to changes over time. In addition, multiple building logistics calculators exist, which can already predict the number of logistics activities that will be needed. Therefore, we recommend linking the planning software and building logistics calculator via the construction logistics module. To support the strategic CLCT, public environmental data and traffic models are available in some countries via local and governmental APIs, such as in Amsterdam. Data on emission zones, traffic, and certain construction activities is public. Governments can provide data on the status of roads and (historical) traffic intensities. These can be used with the traffic management module in the CLCT to minimize hindrance.

[4] See DEFLog, iShare and BDI Network

4.5. Operational construction logistics control tower

The second part of the CLCT is the operational CLCT, which differentiates itself from the strategic CLCT by focusing more on transportation and short-term operational decision-making. We recognize five modules in the operational CLCT: transportation insights, transportation intelligence, water transportation, construction planning and interface. We discuss each further in this section, but first, we explain the main business processes that the operational CLCT should support for (construction) companies.

4.5.1. The supported business processes

Fig. 3 portrays a stylized example of a construction transport process in the upper business layer. We mention stylized explicitly because the chronological order in the example is, in reality, often one with multiple feedback loops because of replanning or delays. The process shows the trigger of transportation planning (*i.e.*, receiving an order or fulfilling an earlier order) to the finalizing of the planning while, in the end, delivering the order on-site, including a delivery note. The operational CLCT focus should be on facilitating this transportation process as well as possible.

4.5.2. Core functionality

The operational CLCT (see Fig. 4) has two core modules, the transportation insights and transportation intelligence modules, which contribute to the system's primary functioning. The transportation insights module's main goal is to show all data and information available related to current transport, capacity of transport and visualizing popular routes. It uses data from transport systems (*i.e.*, Transport Management Systems) and additional sources (*e.g.*, AIS data, governmental data). The module only focuses on showing information; the transport intelligence module is necessary for optimization. This module contains algorithms recognizing collaboration opportunities for combining partial loads into one. Next, the module generates new routes and

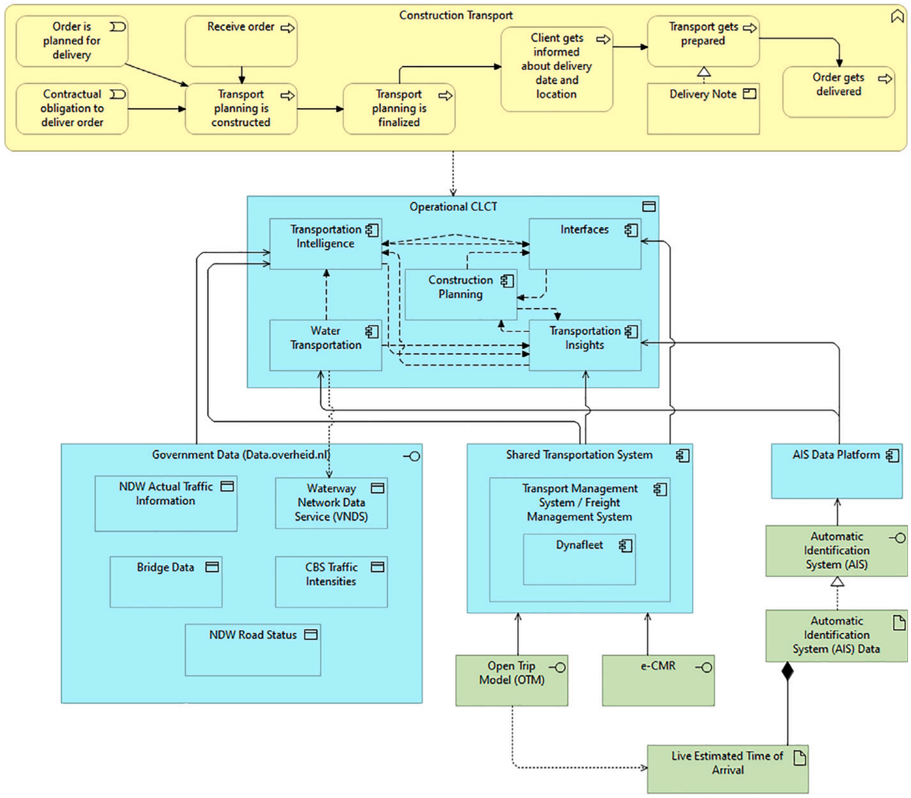

Fig. 3. Operational CLCT and its technologies.

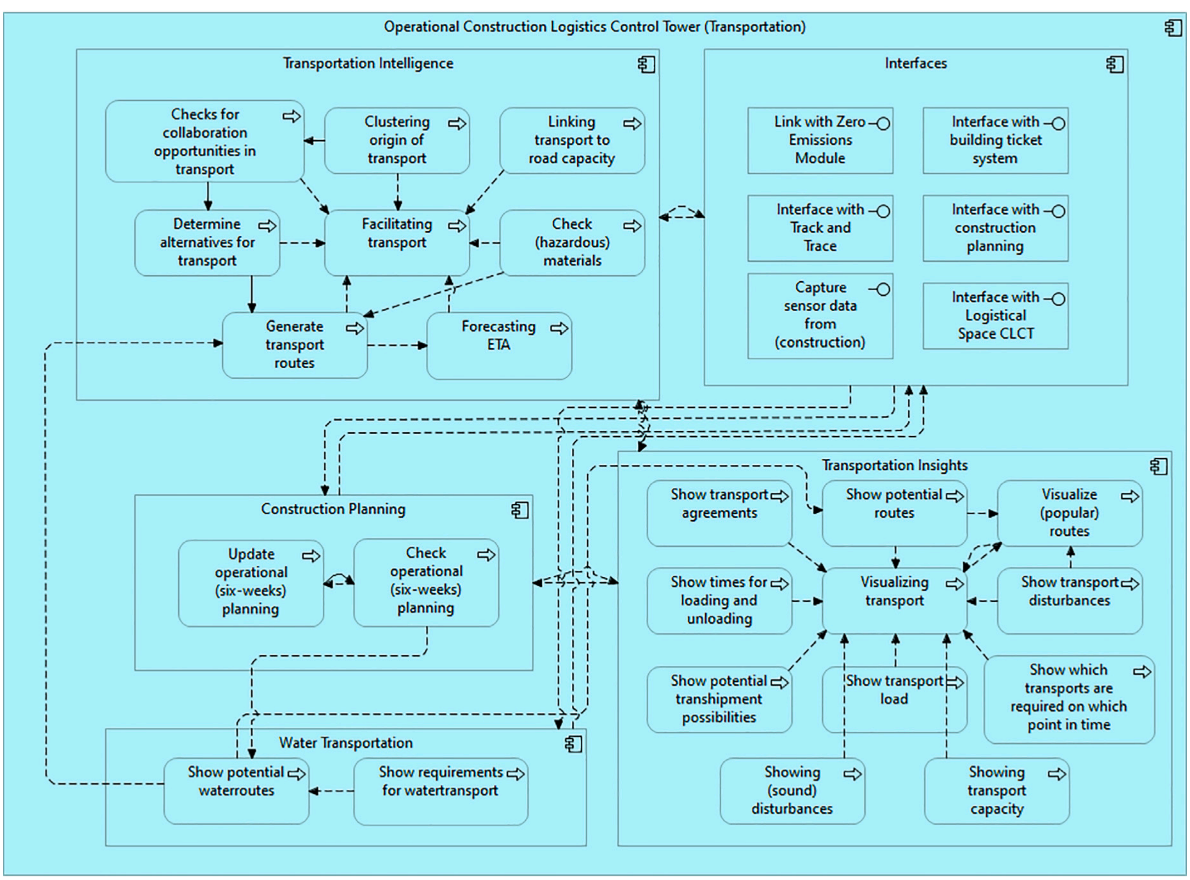

Fig. 4. Operational CLCT application and their inner workings.

raises special attention to special types of materials, such as potentially hazardous materials. Therefore, this module should help multiple stakeholders to collaborate on their transportation activities. It does this by checking the in-place transportation agreements (*i.e.*, contracts of future transportation activities) and looking for opportunities.

The water transportation module is a specific module that aligns with the transportation insights and intelligence modules. Here, data on transportation over water is collected and made functional (*i.e.*, adding the waterways and requirements, therefore, as transportation alternatives if an (inner-)city has this possibility). Most important is that it distinguishes water routes from road-based transportation. The bridge between the strategic CLCT and operational CLCT occurs within the construction planning module. The module retrieves information from long-term planning but also gets information from operational (six-week) planning, in which transportation activities are often more precise. The operational CLCT feeds them to the other modules (*i.e.*, transportation insights and intelligence) but also internally checks and updates the planning based on new insights.

The final module of the operational CLCT is an interface to external data and systems. The operational CLCT needs to get information from external sources to feed the information shown on the screen. Most transportation companies deploy a track and trace system, which allows them to show their fleet in real-time. For an operational transportation CLCT, this information is essential to show the current status of the transport. A zero-emission module could also help determine a potential modal shift or emission reduction by applying different transportation resources (*e.g.*, zero-emission vehicles). The operational CLCT also needs to link to building ticket systems and construction planning and support a potential future logistical space CLCT, which could assist in showing the end-user whether there is enough space in the construction area for transportation. Lastly, the interface with municipality data and systems, such as budgets and contracts, is crucial.

In validating the operational CLCT for the Amsterdam case, we focus on the transportation intelligence and water transportation modules. For the transportation intelligence module, we specifically focus on bundling and combining transports, synchronizing and reducing return transports by introducing circular reuse of pavement at the same location. While also looking at the water transportation module, the timing of this module was typically found late in the process, and the same was valid for the intelligence module. At least it should be anticipated by a similar module in the strategic CLCT since the modal shift and reduction of heavy transport have been the strategic aims of the city for reasons of sustainability, air quality, accessibility, conservation, and liveability.

4.5.3. The supporting technologies

As with the strategic CLCT, the operational CLCT has a set of technologies that support it. Again, public data from the government can show the current status of the roads, waterways and additional infrastructures such as bridges, traffic intensities, and technical status of the roads. However, the most important thing is that the operational CLCT needs to link to third-party transportation systems. These systems are transport management systems (TMS) or freight management systems (FMS) and should link to the operational CLCT. The CLCT itself could function as a shared transportation system, but there are also initiatives in which transporters link their systems. These systems should support standards like the Open Trip Model (OTM)[5] and e-CMR, such as the digital signing of transportation delivery. The water transportation AIS data, which is relatively easy to get and implement, should be used.

Combining CLCTs and their technologies also creates opportunities for construction logistics companies. Some of these will be further developed and implemented for individual companies involved, while others are still a glimpse of what will be possible. In the next section, we discuss the three key technologies supporting the CLCT, which should, from our functional perspective, be the basis for integration in the future.

5. Recommendations on three key technologies

In the previous section, we introduce and design the business environment of the CLCTs, as well as their functionality and interdependencies. However, to realize such a system, one needs certain technologies, which we link to the total design of the CLCT in the last part of the previous section. According to the results from the workshop, some of these technologies are more important than others, including interdependencies and other technologies. We recognize three critical technologies for a CLCT: (4D) Building Information Modelling (BIM), Geographic Information Systems (GIS), and Transportation Management Systems (TMS).

BIM is important as it is the building block for all construction-related activities because the model often represents a digital version of the construction asset, from which much relevant information is derivable. GIS is necessary, as it provides the context to place construction information (*e.g.*, BIM) in a geographical location. In other words, GIS facilitates terrain data and can interact with TMS and BIM to provide data these systems would not possess. Finally, TMS is necessary, as logistics needs transport to get construction materials from A to B. TMS gives insights into the most optimal way to transport materials but could also interact with GIS (where to transport) and BIM (what to transport).

Different companies often adopt these three technologies because of their practical relevance for the individual companies. However, the idea of the CLCT is an inter-organizational system in which these systems can communicate and deliver additional functionality to their traditional form. We discuss these technologies, their definitions, and their historical context. Next, we look for the opportunities that the individual or combined use of the technologies provides for construction logistics companies. We then discuss how the synergy in these technologies can be exploited by linking technologies together. To finish, we discuss potential bottlenecks, opportunities, and recommendations to stimulate the development of a CLCT.

The first of the three technologies is BIM; BIM is a relatively new term, but it has evolved from predecessors like Building Description Systems in the 1970s to Building Product Models in the 1980s to Generic Building Models in the 1990s until BIM was the popular term (Latiffi et al., 2014). However, multiple definitions of BIM exist, and even alternative namings exist, such as Building Information Management. Most often, people working with BIM see it as a digital model of a construction asset that combines information about the construction project (Doan et al., 2019).

The second technology is GIS, and Geographic Information System has similar issues regarding a clear definition. Multiple definitions exist (c.f. Maguire (1991)), ranging from "an information technology which stores, analyses, and displays both spatial and non-spatial data "(Cooperative and Collins, 1988) to "a decision support system involving the integration of spatially referenced data in a problem-solving environment" (Cowen, 1990) to finally "a system for capturing, storing, checking, manipulating, analysing and displaying data which are spatially referenced to the earth" (DoE, 1987).

The third and final technology is TMS, a Transport Management System broadly applied in practice. However, in literature, compared to the earlier two mentions, there needs to be more discussion, let alone a clear definition of what such a system is. Nevertheless, a TMS facilitates companies in handling transportation processes and is usually, but only sometimes, linked to a more extensive Enterprise Resource Planning system. The main goal of a TMS is to plan, follow and help execute transportation activities. It can also inform customers about the current status of the transport. For larger transportation companies that offer

[5] OpenTripModel

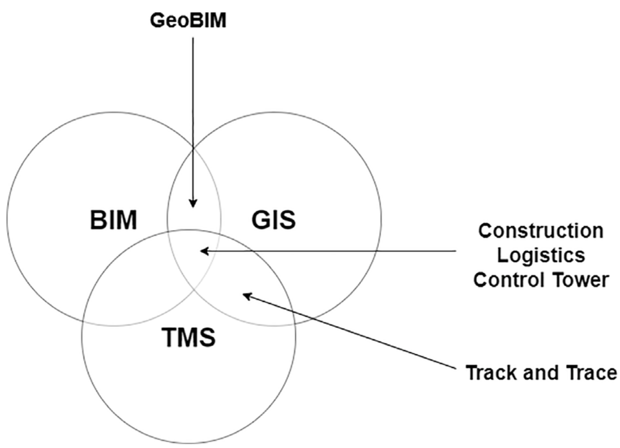

Fig. 5. CLCT key technologies.

a transportation service to other companies or organizations, such a system is their key IT asset.

The combination of those technologies is essential to construct a CLCT in practice. However, why should stakeholders include or link these individual IT systems inter-organizationally? Literature provides us with some relevant and exciting applications of combinations of the key technologies. For construction, BIM has provided many opportunities to optimize construction scheduling and other multi-objective performance-related issues (c.f., Asl et al. (2015), Essam et al. (2023)). However, to apply these solutions, a certain level of BIM maturity is needed, and assessments exist to help determine the maturity of BIM in companies (*e.g.*, Chen et al. (2023)). If such maturity is present, BIM could also assist in different aspects.

BIM and all dimensional variations (*i.e.*, 3D BIM for 3D models, 4D BIM includes modelling scheduling information, 5D BIM includes financial costs, etc.) are applicable for different purposes. 4D BIM could help in reducing transportation waste (Pérez and Costa, 2019). BIM is also a reasonable basis for estimating vertical transportation (*i.e.*, using cranes) activities (Wu et al., 2020). Another perspective is optimizing material and construction layout planning (c.f., Cheng and Chang (2019), Tao et al. (2022)). So, the link between optimizing logistics and transportation activities regarding construction is addressed in the literature (*e.g.*, Pérez et al. (2016)) and practice (*e.g.*, Whitlock et al. (2018))

New opportunities are in combining the technologies mentioned earlier. For TMS, we need more evidence in the literature on applications in which TMS combines with BIM technology. However, such a link should be there from the perspective of 4D BIM (*i.e.*, including scheduling information). We do find literature that discusses potential opportunities for BIM and GIS combinations. A literature review by Fosu et al. (2015) discusses that research on integrating BIM and GIS for different applications has been taking place for years, for example, asset management, and could even increase the success of asset management (Fosu et al., 2015). Other applications are on supply chain management (*e.g.*, Deng et al. (2019), Irizarry et al. (2013)), optimizing construction site layouts (*e.g.*, Zavari et al. (2022)) and traffic planning (*e.g.*, Wang et al. (2014)). The combination of BIM and GIS, BIM and TMS, GIS and TMS and all three provide some opportunities for the construction logistics supply chain.

In Fig. 5, we see the combination of the multiple vital technologies that support and execute the CLCT in its whole essence. Individual applications are already taking place at organizations; for example, construction companies usually apply BIM, GIS is popular under public organizations (*e.g.*, municipalities using it for cadastral purposes), and transportation companies mainly use TMS. One could say that linking these should be vital in facilitating the functioning of a CLCT. There are some examples of combinations in practice. BIM and GIS are combined in systems and defined as GeoBIM. GIS is often used in TMS systems to visualize the current state of transport (*i.e.*, track and trace) with the help of GPS technology. The combination of BIM and TMS is an addition to 4D BIM but is ill-defined in literature and practice. However, combining the three technologies is a unique classification of the CLCT application.

However, setting up such a CLCT system and integrating the three technologies is problematic as many stakeholders, often with different interests, need to implement it. Additionally, we see four other problems that need tackling before such a system can exist. First, digitalization is limited, especially in construction companies, as they do not see the registration and utilization of data and information as their core business. This lack of digitalization can change positively by applying new technologies like artificial intelligence that limit the amount of human input needed to realize such things. Second, in inter-organizational collaborations, it is advised to have a leading organization, which is often hard to determine due to conflicting interests. We could solve this by taking a decentralized approach to setting up CLCT, in which the system is not centrally organized but linked together decentrally.

However, this implies that decentralized links should be available. This implication brings us to the third potential hurdle. The lack of Application Programming Interfaces (APIs). These APIs are well suited for sending and receiving data from IT systems, but often, they are absent in legacy systems. Access is usually strictly guarded by the organization owning the system if they are available. However, from other industries (*e.g.*, the financial sector), it is known that opening up these APIs could generate additional business. As a potential solution, the construction industry could deploy a similar solution to the Payment Services Directive 2 (*i.e.*, a European Union directive stating that financial institutions are mandated to open their IT systems by creating open APIs). Governmental organizations could consider such a solution for construction projects, which has been the case from a legal perspective by mandating BIM for public projects in the UK (Davies and Harty, 2012). However, mandating this could also result in resistance and limit enforceability in practice (Davies and Harty, 2012). Economic incentives are often lacking and, therefore, fail to end the potential hurdles, especially in linking these systems, as they require additional capacity from organizations for which the direct benefits could be more evident. Making direct benefits more evident by valuing data from an economic perspective and exploring new business cases for inter-organizational collaboration solves this.

6. Conclusion and discussion

The construction industry has ample opportunity to improve, optimize, and integrate its logistics processes. In this paper, we discussed the application of a CLCT artefact for the construction industry with a case from the inner city of Amsterdam. We explored the potential need for a CLCT from the perspective of different stakeholders and applied a co-creation approach to develop different types of CLCT. We consider four types of CLCT, but eventually, we narrow them to two. Ultimately, only one type, *i.e.*, a transportation-focused CLCT, is developed into a core diagram (*i.e.*, a reference architecture with primary functionality).

We recognize two versions of the transportation CLCT, *i.e.*, a strategic version that prioritizes long-term planning and an operational version that adapts to more day-to-day processes. We discuss the critical applications within both versions and their link to the available business processes and technologies. From these technologies available, we derive three key technologies for a CLCT, *i.e.*, Building Information Modelling, Geographic Information System and Transportation Management System. For each, we describe potential benefits for the construction logistics process for technology combinations. Additionally, we discuss potential hindrances and opportunities in implementing the CLCT and integrating the three technologies and provide solutions for them. In the case study presented in this paper, a manual approach to the CLCT has shown clear opportunities for improving transport efficiency and sustainability and reducing the hindrance of transport for concurrent projects in an urban area.

Additionally, this paper adds a theoretical development of control tower(s) in the construction (logistics) industry. The reference architecture for the strategic and operational CLCT is a blueprint for the industry to start intensifying supply chain coordination. For academics, this reference architecture could be the basis for research into different configurations and studies into the efficiency and effectiveness of individual modules. Our core diagram is a valuable starting point for practitioners to develop individual components of a CLCT. However, it does not tell practitioners how to develop these in detail and lacks if they are feasible. This lack of detail is both an advantage and disadvantage; practitioners still need to find out how these modules should operate, but on the contrary, the reference architecture also gives them this freedom.

This CLCT research has also amplified doubts about IT and data maturity in the construction sector. It is well-known that the construction industry has issues digitizing its business processes. However, this is problematic for a CLCT application, as it requires intermediate to advanced maturity levels. Further research should address some of the pinpoints we provided in earlier sections. Nevertheless, an industry or culture will not change by mandating this change top-down. Bottom-up change is also needed by focusing on the economic interests of construction companies.

Suppose construction companies have better business models and ways to value these systems and their data, or the government forces sustainability requirements. In that case, this might open up the deadlock. One could think of methods like value mapping to show potential waste savings with the help of IT. An alternative method combines data valuation with game theoretical models to decide whether creating, facilitating, and sharing data benefits individual organizations. However, such methods should be approachable and generalizable to multiple cases easily. The top-down and bottom-up approaches need investigation into their success rates in a broader context, including the effect of externalities.

CRediT authorship contribution statement

Rogier Harmelink: Writing – review & editing, Writing – original draft, Visualization, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Siem van Merrienboer:** Writing – review & editing, Methodology, Funding acquisition, Data curation, Conceptualization. **Arjen Adriaanse:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Jos van Hillegersberg:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Engin Topan:** Writing – review & editing, Supervision. **Ruben Vrijhoef:** Writing – review & editing, Validation, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors thank the three independent reviewers for their critical reviews, which have helped us improve the manuscript's quality indefinitely.

This research has been funded by TKI Dinalog, The Netherlands under the project name "Fundaments of a Construction Logistics Control Tower (CLCT) 2023", award number 060.49774.

Data availability

Data will be made available on request.

References

Appelbaum, S.H., 1997. Socio-technical systems theory: an intervention strategy for organizational development. Manag. Decis. (ISSN: 0025-1747) 35 (6), 452–463.

Asl, M.R., Zarrinmehr, S., Bergin, M., Yan, W., 2015. BPOpt: A framework for BIM-based performance optimization. Energy Build. (ISSN: 0378-7788) 108, 401–412.

Baumgrass, A., Dijkman, R., Grefen, P., Pourmirza, S., Völzer, H., Weske, M., 2014. A software architecture for a transportation control tower. Tech. Univ. Eindh. Tech. Rep. Beta Work. Pap. Ser. 461.

Bleda, J., Martin, R., Narsana, T., Jones, D., 2014. Prepare for takeoff with a supply chain control cower enabling technologies for supply chain control towers.

Bloomberg, J., 2014. Is enterprise architecture completely broken. Forbes Mag..

Briscoe, G., Dainty, A., 2005. Construction supply chain integration: an elusive goal? Supply Chain Manag. (ISSN: 1359-8546) 10 (4), 319–326.

Brusselaers, N., Mommens, K., Janné, M., Fredriksson, A., Venås, C., Flyen, C., Fufa, S.M., Macharis, C., 2020. Economic, social and environmental impact assessment for off-site construction logistics: the data availability issue. In: IOP Conference Series: Earth and Environmental Science. Vol. 588, (3), IOP Publishing, 032030, ISBN: 1755-1315.

Casini, M., 2022. Chapter 8 - Advanced building construction methods. In: Casini, M. (Ed.), Construction 4.0. Woodhead Publishing, ISBN: 978-0-12-821797-9, pp. 405–470. http://dx.doi.org/10.1016/B978-0-12-821797-9.00006-4, URL https://www.sciencedirect.com/science/article/pii/B9780128217979000064.

Chen, Z.-S., Zhou, M.-D., Chin, K.-S., Darko, A., Wang, X.-J., Pedrycz, W., 2023. Optimized decision support for BIM maturity assessment. Autom. Constr. (ISSN: 0926-5805) 149, 104808.

Cheng, M.-Y., Chang, N.-W., 2019. Dynamic construction material layout planning optimization model by integrating 4D BIM. Eng. Comput. (ISSN: 0177-0667) 35, 703–720.

Cooperative, G., Collins, F., 1988. The unique qualities of a geographic information system: a commentary. Photogramm. Eng. Remote Sens. 54 (11), 1547–1549.

Cowen, D.J., 1990. GIS versus CAD versus DBMS: what are the differences? In: Introductory Readings in Geographic Information Systems. CRC Press, pp. 70–80.

Dainty, A.R.J., Millett, S.J., Briscoe, G.H., 2001. New perspectives on construction supply chain integration. Supply Chain Management: An Int. J. (ISSN: 1359-8546) 6 (4), 163–173.

Dalmolen, S., Moonen, H., van Hillegersberg, J., 2015. Towards an information architecture to enable cross chain control centers. Cross- Chain Collab. the Fast Mov. Consum. Goods Supply Chain, Univ. Eindh. 111–122.

Davies, R., Harty, C., 2012. Control, surveillance and the 'dark side' of BIM. In: Smith, S.D. (Ed.), Proceedings of the 28th Annual ARCOM Conference, Edinburgh, UK. Association of Researchers in Construction Management, London, UK.

De Bes, J., Eckartz, S., Van Kempen, E., Van Merrienboer, S., van Amstel, W.P., Van Rijn, J., Vrijhoef, R., 2018. Duurzame bouwlogistiek voor binnenstedelijke woning-en utiliteitsbouw: ervaringen en aanbevelingen.

Deng, Y., Gan, V.J.L., Das, M., Cheng, J.C.P., Anumba, C., 2019. Integrating 4D BIM and GIS for construction supply chain management. J. Constr. Eng. Manag. (ISSN: 0733-9364) 145 (4).

Doan, D., Ghaffarianhoseini, A., Naismith, N., Zhang, T., Tookey, T., 2019. What is BIM? A need for a unique BIM definition. In: International Conference on Built Environment and Engineering 2018 - "Enhancing Construction Industry Through IR4.0" (IConBEE2018). EDP Sciences, (ISSN: 2261-236X).

DoE, 1987. Handling geographic information. Tech. rep., HMSO London.

Essam, N., Khodeir, L., Fathy, F., 2023. Approaches for BIM-based multi-objective optimization in construction scheduling. Ain Shams Eng. J. (ISSN: 2090-4479) 14 (6), 102114.

Fosu, R., Suprabhas, K., Rathore, Z., Cory, C., 2015. Integration of Building Information Modeling (BIM) and Geographic Information Systems (GIS) – a literature review and future needs. In: Proceedings of the 32nd CIB W78 Conference, Eindhoven, the Netherlands. pp. 27–29.

Harmelink, R., 2022. Constructing the service control tower.

Irizarry, J., Karan, E.P., Jalaei, F., 2013. Integrating BIM and GIS to improve the visual monitoring of construction supply chain management. Autom. Constr. (ISSN: 0926-5805) 31, 241–254.

Janné, M., Fredriksson, A., 2022. Construction logistics in urban development projects – learning from, or repeating, past mistakes of city logistics? Int. J. Logist. Manag. (ISSN: 0957-4093) 33 (5), 49–68.

Kotusev, S., 2016. Different approaches to enterprise architecture. J. Enterp. Archit. 12 (4), 9–16.

Latiffi, A.A., Brahim, J., Fathi, M.S., 2014. The development of building information modeling (BIM) definition. Appl. Mech. Mater. (ISSN: 1662-7482) 567, 625–630.

Löhe, J., Legner, C., 2014. Overcoming implementation challenges in enterprise architecture management: a design theory for architecture-driven IT Management (ADRIMA). Inf. Syst. E- Bus. Manag. (ISSN: 1617-9846) 12, 101–137.

Maguire, D.J., 1991. An overview and definition of GIS. Geogr. Inf. Systems: Princ. Appl. 1, 9–20.
Meekings, A., Briault, S., 2013. The "control tower" approach to optimising complex service delivery performance. Meas. Bus. Excel. (ISSN: 1368-3047).
Meissner, C., 2015. Trust building in logistics cooperations: A conceptual model for the design of a trust-building control tower strategy in multi-company cooperations in logistics.
Milenković, M., Bojović, N., Val, S., 2019. A value case approach for improving the quality of rail freight services: control tower concept. In: 8th International Symposium and 30th National Conference on Operational Research. pp. 140–146.
Mohammad, N.A., Mohd Azani, M.F., 2018. Malaysia's experience in integrated co-ordination of offshore supply vessels through Integrated Logistics Control Tower ILCT. In: SPE Asia Pacific Oil and Gas Conference and Exhibition. Society of Petroleum Engineers, Brisbane, Australia, ISBN: 1613995954, http://dx.doi.org/10.2118/191928-MS.
Naji, K.K., Gunduz, M., Alhenzab, F.H., Al-Hababi, H., Al-Qahtani, A.H., 2024. A systematic review of the digital transformation of the building construction industry. IEEE Access (ISSN: 2169-3536) 12, 31461–31487. http://dx.doi.org/10.1109/ACCESS.2024.3365934.
O'Brien, W., 1999. Construction Supply-Chain Management: A vision for advanced coordination, costing, and control.
Oosterwijk, L., 2017. Supply Chain Management with BIM: Towards better control of construction logistics.
Papadopoulos, G.A., Zamer, N., Gayialis, S.P., Tatsiopoulos, I.P., 2016. Supply chain improvement in construction industry. Univers. J. Manag. 4 (10), 528–534.
Peiris, P.A.N., Hui, F.K.P., Ngo, T., Duffield, C., Garcia, M.G., 2023. Challenges in transport logistics for modular construction: A case study. In: Dissanayake, R., Mendis, P., Weerasekera, K., De Silva, S., Fernando, S., Konthesingha, C. (Eds.), 12th International Conference on Structural Engineering and Construction Management. Lecture Notes in Civil Engineering, Vol 266. Springer, Singapore, pp. 501–510.
Pérez, C.T., Costa, D.B., 2019. Evaluation of 4D BIM use to reduce transportation waste in construction production processes. Simpósio Bras. de Gestão e Econ. Da Construção (ISSN: 2764-1600) 11, 1–7.
Pérez, C.T., Fernandes, L.L.A., Costa, D.B., 2016. A literature review on 4D BIM for logistics operations and workspace management. In: Proceedings of the 24nd International Group of Lean Construction. pp. 486–495.
Prahalad, C.K., Ramaswamy, V., 2000. Co-opting customer competence. Harv. Bus. Rev. (ISSN: 0017-8012) 78 (1), 79–90.
Ramaswamy, V., Ozcan, K., 2018. What is co-creation? An interactional creation framework and its implications for value creation. J. Bus. Res. (ISSN: 0148-2963) 84, 196–205.
Rood, M.A., 1994. Enterprise architecture: definition, content, and utility. In: Proceedings of 3rd IEEE Workshop on Enabling Technologies: Infrastructure for Collaborative Enterprises. IEEE, Morgantown, WV, USA, ISBN: 0818657057, pp. 106–111.
Ross, J.W., Weill, P., Robertson, D., 2006. Enterprise Architecture as Strategy: Creating a Foundation for Business Execution. Harvard Business School Press, Boston, Massachusetts, ISBN: 1422148173.
Sezer, A.A., Fredriksson, A., 2021. Paving the path towards efficient construction logistics by revealing the current practice and issues. Logistics (ISSN: 2305-6290) 5 (3), 53.
Staring, R.J., 2019. Cross-project collaboration in the construction sector: a 4C control tower for construction supply chains.
Sundquist, V., Gadde, L.-E., Hulthén, K., 2018. Reorganizing construction logistics for improved performance. Constr. Manag. Econ. (ISSN: 0144-6193) 36 (1), 49–65.
Tao, G., Feng, H., Feng, J., Wang, T., 2022. Dynamic multi-objective construction site layout planning based on BIM. KSCE J. Civ. Eng. (ISSN: 1226-7988) 26 (4), 1522–1534.
Tesselaar, T., 2020. Designing a construction logistics control tower for city development: A case study in Amsterdam Amstel III.
Thompson, J.D., 2017. Organizations in Action: Social Science Bases of Administrative Theory. Routledge, New York, ISBN: 1315125935.
Topan, E., Eruguz, A.S., Ma, W., van der Heijden, M.C., Dekker, R., 2020. A review of operational spare parts service logistics in service control towers. European J. Oper. Res. (ISSN: 03772217) 282 (2), 401–414. http://dx.doi.org/10.1016/j.ejor.2019.03.026.
Trzuskawska-Grzesińska, A., 2017. Control towers in supply chain management–past and future. J. Econ. Manag. (ISSN: 1732-1948) 27, 114–133.
van Merriënboer, S., Meijer, L., Rondaij, A., Harmelink, R., Vrijhoef, R., Adriaanse, A., 2023. Control towers in de bouwlogistiek, een verkenning van ketenregie.
Venås, C., Flyen, C., Fufa, S.M., Janné, M., Fredriksson, A., Brusselaers, N., Mommens, K., Macharis, C., 2020. No or low emissions from construction logistics – Just a dream or future reality? In: IOP Conference Series: Earth and Environmental Science. 588, (4), IOP Publishing, 042003, ISBN: 1755-1315.
Vlachos, I., 2023. Implementation of an intelligent supply chain control tower: a socio-technical systems case study. Prod. Plan. Control (ISSN: 0953-7287) 34 (15), 1415–1431.
Vrijhoef, R., Harmelink, R., 2024. Control tower approach to improve urban construction logistics. In: Skibniewski, M.J., Hajdu, M. (Eds.), Creative Construction Conference, CCC 2024. Budapest University of Technology and Economics, Prague, http://dx.doi.org/10.3311/CCC2024-091.
Vrijhoef, R., Koskela, L., 1999. Roles of supply chain management in construction. URL https://api.semanticscholar.org/CorpusID:13247343.
Wang, J., Hou, L., Chong, H.-Y., Liu, X., Wang, X., Guo, J., 2014. A cooperative system of GIS and BIM for traffic planning: A high-rise building case study. In: Cooperative Design, Visualization, and Engineering: 11th International Conference, CDVE 2014, Seattle, WA, USA, September 14-17, 2014. Proceedings 11. Springer, ISBN: 3319108301, pp. 143–150.
Whitlock, K., Abanda, F.H., Manjia, M.B., Pettang, C., Nkeng, G.E., 2018. BIM for construction site logistics management. J. Eng. Proj. Prod. Manag. (ISSN: 2221-6529) 8 (1), 47–55.
Wieringa, R.J., 2014. Design Science Methodology for Information Systems and Software Engineering. Springer, ISBN: 3662438399.
Wu, K., de Soto, B.G., Adey, B.T., Zhang, F., 2020. BIM-based estimation of vertical transportation demands during the construction of high-rise buildings. Autom. Constr. (ISSN: 0926-5805) 110, 102985.
Ying, F., Tookey, J., Seadon, J., 2018. Measuring the invisible: A key performance indicator for managing construction logistics performance. Benchmarking: An Int. J. (ISSN: 1463-5771) 25 (6), 1921–1934.
Yu, Y., Yazan, D.M., van den Berg, M., Firdausy, D.R., Junjan, V., Iacob, M.-E., 2023. Circularity information platform for the built environment. Autom. Constr. (ISSN: 0926-5805) 152, 104933. http://dx.doi.org/10.1016/j.autcon.2023.104933, URL https://www.sciencedirect.com/science/article/pii/S0926580523001930.
Zavari, M., Shahhosseini, V., Ardeshir, A., Sebt, M.H., 2022. Multi-objective optimization of dynamic construction site layout using BIM and GIS. J. Build. Eng. (ISSN: 2352-7102) 52, 104518.