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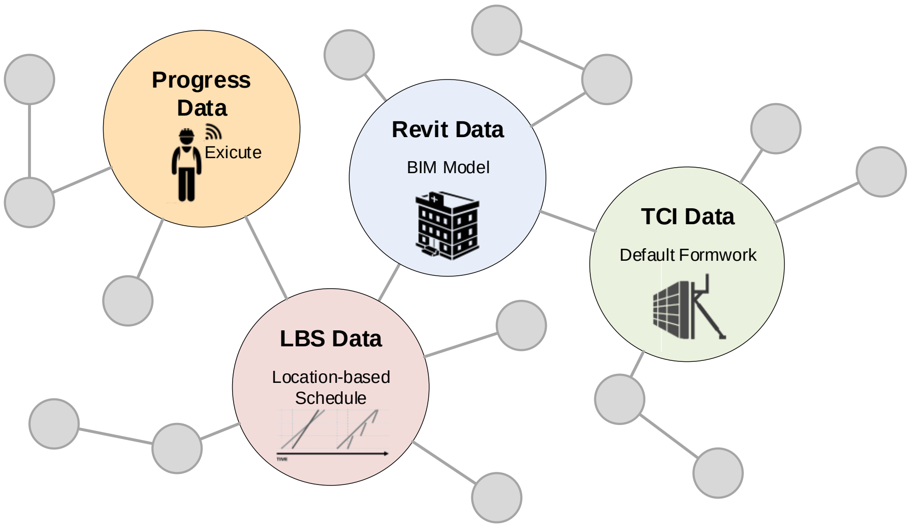

Unlocking the value of Linked Building Data (LBD)
A lean and integrated management process of temporary construction items (TCIs)

MASTER THESIS

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Abstract

In recent years the construction industry has experienced poor productivity and safety issues at construction sites due to scarce technological developments and a working culture of silos. This has led to discontinued information flows and a lack of transparency in the construction process. Even though new technological innovations have the potential to overcome these challenges, the main focus lies currently with permanent construction, leading to a lack of attention on temporary construction items (TCIs). Hence, this paper addresses the poor planning and management of TCIs and aims at developing a solution to close this gap.

Following the guidelines for developing an innovation, this paper examines the automatic consideration of TCIs in both the planning and execution of construction projects. After identifying current challenges, the objective of this paper is to outline a project delivery system with a lean and integrated management process that improves productivity and safety at construction sites. By utilizing Linked Data technologies for the explored data value chain, the paper continues the path of a growing number of researchers, aiming at unlocking the value of Linked Building Data (LBD). Through findings from literature, expert interviews as well as a construction site observation, a concept solution is developed. By consequently narrowing down the theoretical concept to the scope of formwork utilization and applying the concept to a two-folded prototyping process, including a demo project and case study, the theoretical solution is iteratively put into practice. As the prototype integrates data from Building Information Modelling (BIM), Location-Based Scheduling (LBS) and TCI information into a Linked Data environment, the precise TCI demand for the construction site can be calculated. Resulting in a functioning solution for automatically creating a time- and location-based TCI utilization plan for the entire construction project, allowing an efficient and lean management of these items, the paper subsequently confirms the potential of the developed solution as well as determines its limitations by conducting evaluation interviews with experts from the industry. Based on the results of prototyping and findings from the interviews, this research study integrates the solution into the process of construction and finally presents two implementation scenarios for the solution – one being based on the current industry situation and one exploring the future vision of a more integrated and decentralized project delivery in the construction industry.

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List of Abbreviations

5G	Fifth-generation technology standard for cellular networks
ACI	American Concrete Institute
AI	Artificial Intelligence
API	Application Programming Interface
ASCE	American Society of Civil Engineers
BBB	Bridging BIM and Building
BIM	Building Information Modelling
BLE	Bluetooth Low Energy
BOT	Building Topology Ontology
CLM	Construction Logistics Management
GDP	Gross Domestic Product
GIS	Geographic Information System
GPS	Global Positioning System
GUID	Globally Unique Identifier
HTTP	Hypertext Transfer Protocol
ICT	Information and Communications Technology
IHSA	Infrastructure Health & Safety Association
IoT	Internet of Things
ISO	International Organization for Standardization
IT	Information Technology
KPI	Key Performance Indicator
LBD	Linked Building Data
LBMS	Location-Based Management System
LBS	Location-Base Scheduling
LPS	Last Planner System
OSHA	Occupational Safety and Health Administration
PCI	Permanent Construction Items
PPC	Planned Percent Complete
R&D	Research & Development
RDF	Resource Description Framework
RFID	Radio Frequency Identification
RQ	Research Question
SCP	Smart Construction Planner
SHACL	Shapes Constraint Language
SMEs	Small and Medium-Sized Enterprises
SPARQL	SPARQL Protocol and RDF Query Language
SQL	Structured Query Language
SRF	Safety-Risk-Factor
SSFI	Scaffolding, Shoring and Forming Institute
TCI	Temporary Construction Items
URI	Unique Resource Identifier
URL	Unique Resource Locator

Chapter 1: Introduction

"*Soon I'll be running out of space on the job site to put the formwork. Where shall I put the formwork?*"
– Citation of a contractor (cf. Chapter 6.3)

Exemplified by the given quote from a construction site, the current construction industry is facing severe challenges due to non-transparent and inefficient construction planning and management, leading to poor productivity and weak safety considerations in the process of constructing a building. It is almost general knowledge in society that buildings are still built the same way as they have been 50 years ago (World Economic Forum 2016). This example mirrors the current situation in the construction industry, which is often claimed to fall behind the technological development of other industries. Nowadays, the industry suffers from decades of neglecting investments in this area. As a result, poor productivity at a construction site is a major challenge in almost all construction projects around the globe (Barbosa et al. 2017). Another aspect that is highly neglected in construction is safety even though the industry is classified among the most dangerous ones (Zhou et al. 2013). However, an emerging amount of technological innovations that have lately been adopted yield the potential to overcome both productivity and safety issues (Blanco et al. 2017). Implementing these technologies in construction enables the industry to improve the whole life-cycle of a building from design to operation, yet, the highest potential to increase productivity lies in the improvement of the project execution, especially regarding site and logistics management (Barbosa et al. 2017). Integrating new technologies in this field would allow proper management of the dynamic building process with a lean and continuous flow of resources (Whitlock et al. 2018).

Proper planning of resources on a construction site can be achieved by integrating Building Information Modelling (BIM) and Location-Based Scheduling (LBS) for the permanent building parts as they are modelled in a 3D-model. Adding time as another dimension creates a powerful 4D-BIM-plan that fosters the management capabilities of the construction manager. However, this method does not imply the planning of temporary construction items (TCIs). Although these items can highly impact project performance, including productivity and safety, there is a lack of attention regarding proper planning and management of TCIs (Beale and André 2017).

Since TCIs as formwork and supporting structures are relatively cheap, frequently move around the construction site, and are used several times during a project, an integration into BIM has not been addressed yet. Therefore, the consideration of these items is still based on manual work and rough estimations with insufficient knowledge of the workers on a day to day basis at the construction site (Kim et al. 2018).

Motivated by the fact that technologies exist to properly consider TCIs in the construction management process, this research project aims at finding a suitable solution for integrating TCIs in construction planning and management and developing a framework for its application and adoption. By doing that, the research strives to have a positive impact on the technological development as well as on the productivity and safety aspect of the construction industry. The following hypothesis is derived from this motivation and shall guide the thesis through its development.

Hypothesis:

"Existing technologies and methods have the potential to overcome the challenges regarding logistics management of TCIs in the construction industry, and hence improve productivity and safety on site."

For the development of the thesis, a structured approach is used to guide the research from problem identification over the analysis of potential solutions to the development of a specific and implementable solution. First, a brainstorming approach was used to determine the scope of the thesis within the construction industry (Martin and Hanington 2012). Hereby, the developed mind map (**Appendix 1**) addresses and explores both the research scope as well as the scientific frame concerning the research design. Based on the results of the mind map, the structure of the thesis was developed. This structure is displayed in figure 1 and shall help the reader to follow the red thread by covering and summarizing the entire content of this research study. Furthermore, it provides a comprehensive overview of the subsequent steps and chapters of this paper and links together all the research elements in order to facilitate the understanding and information flow.

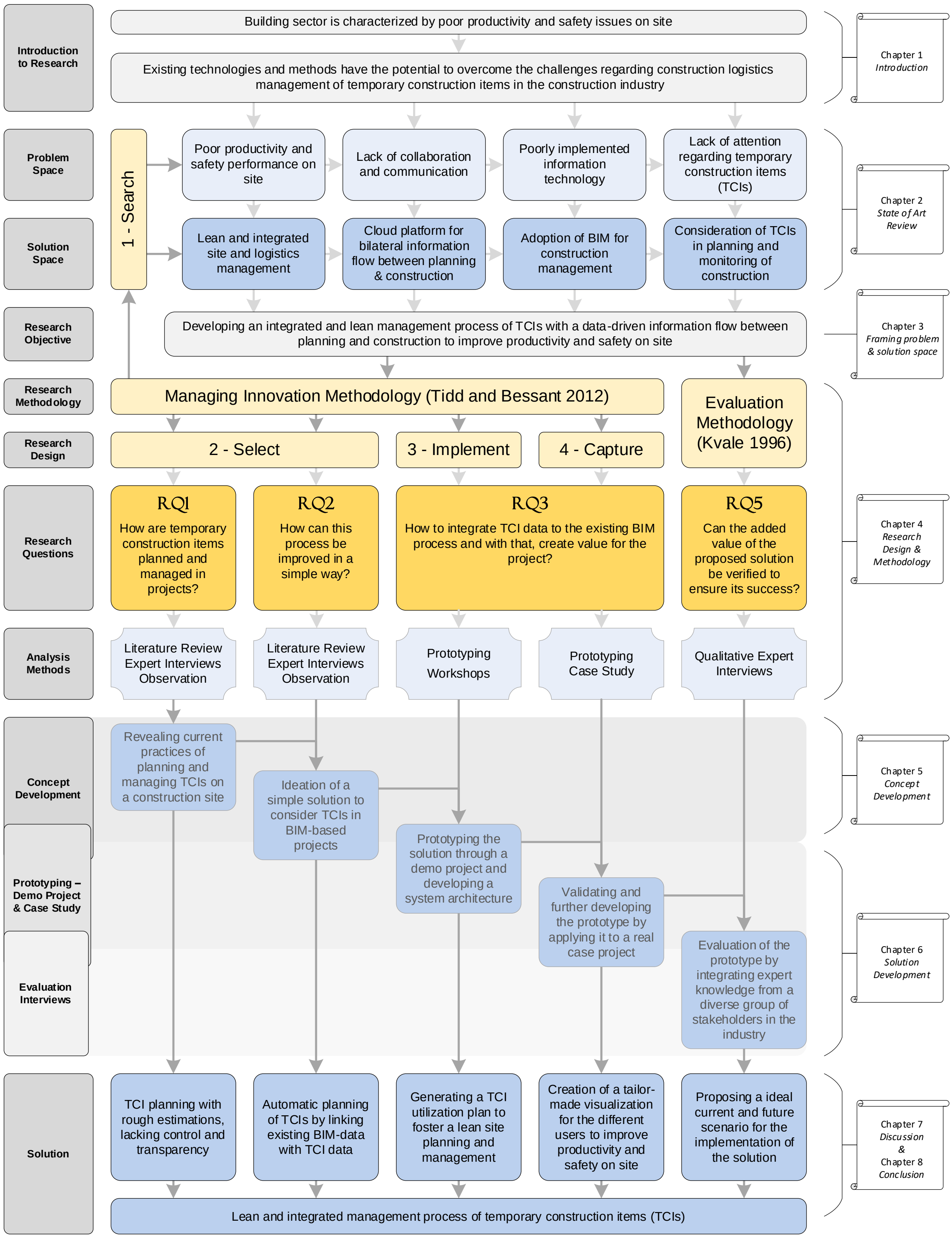


Figure 1: Structure of the research paper (own visualization)

Chapter 2: State of Art Review

In this chapter, a state of art review is conducted aiming to frame the construction industry in its current context by revealing current challenges in the industry and eventually leading to the specific problem definition. Based on these challenges, a number of existing technologies and methods are identified as potential solutions to improve construction performance. Here, the double diamond methodology is applied to guide the research development from early problem analysis towards delivering a functioning solution (Figure 2). The methodology provides this chapter with a verified strategy and different phases to follow. (Heffernan 2017)

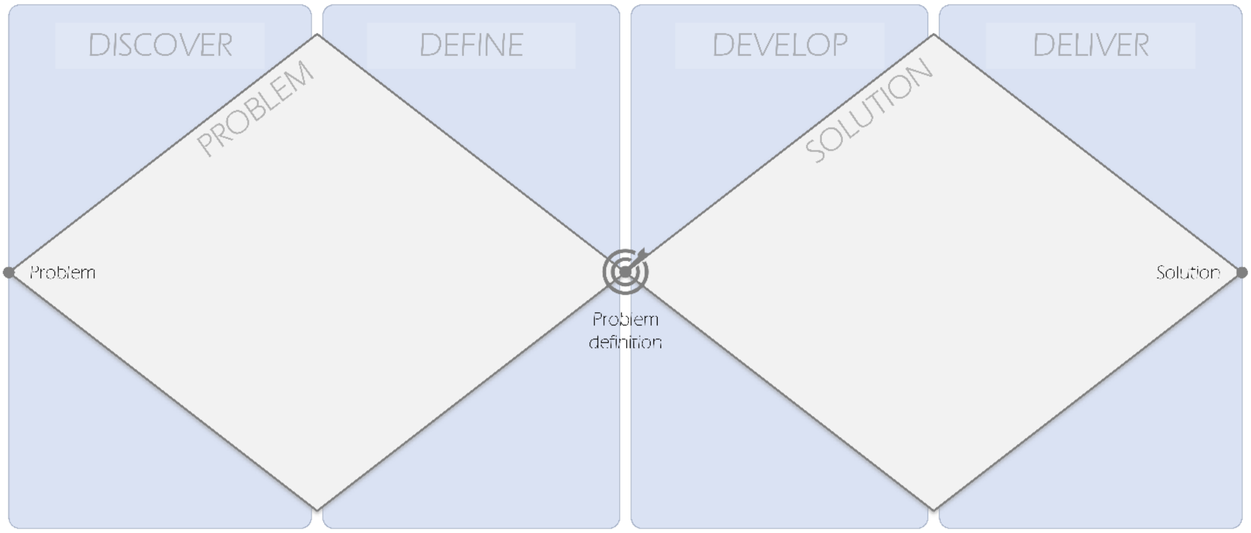


Figure 2: Double Diamond Methodology (own visualization)

The process of revealing relevant challenges and solutions is repeated both from the theoretical as well as from the practical point of view. Firstly, a comprehensive literature analysis is conducted. Hereby, the analysis is facilitated by the use of Citavi, a software for reference and knowledge management in which the explored literature is linked to thesis-specific categories (Swiss Academic Software 2020). This ensures a systematic and structured review of state-of-art literature. Secondly, the practical point of view is covered with the integration of expert knowledge from qualitative interviews (Kvale 1996) to verify scientific findings and introduce the professional experience to this research. Subsequently, the research objective is derived by framing potential technologies towards a specific scope. Defining the research objective will serve as the starting point and basis to define research questions for this academic research project.

2.1 Theoretical Point of View

The construction industry is one of the largest industries in the world, accounting for 13% of the global GDP (Barbosa et al. 2017). Besides its economic influence, the construction industry also plays an important role in society. Construction and infrastructure projects shape everyday life and culture, and offer people opportunities for living, working, and mobility (Lamprecht 2016). For years, however, the construction industry has been suffering from a massive lack of productivity. Compared to other industries, the construction industry is far behind in terms of development (Barbosa et al. 2017). Exploring this statement further, the following section introduces the industry's main challenges yet to be overcome, providing the relevant problem space from a theoretical point of view for the thesis. After identifying the root problems of the construction industry, literature is reviewed for relevant solutions with the potential to improve the industry's current situation.

2.1.1 Problem Space

Productivity is traditionally defined as the ratio between input and output. In the construction industry, this mainly implies the ratio between the use of resources and the created economic value in construction. Reducing the number of resources, utilized to create value, thus is determined as the overall goal to increase construction productivity (Dozzi and AbouRizk 1993). From 2000 to 2011, the productivity of the construction industry in Germany rose by only 4.1%, with the entire economy showing an increase of 11% (Baumanns et al. 2016). According to the World Economic Forum's report "Shaping the Future of Construction", other industries in the USA were able to increase their productivity by 153% between 1964 and 2012. By contrast, the US construction industry lost 19% of its productivity over the same period (World Economic Forum 2016). This phenomenon of decreasing productivity can not only be observed in the USA but has global applicability as the construction industry is losing touch with the productivity and development of other industries, especially to manufacturing (Figure 3). Due to its low productivity index, construction projects are exposed to high risk in terms of cost and time overruns. According to McKinsey (Changali et al. 2015), 98% of big construction projects are facing cost overrun, resulting in an average cost increase of 80%, compared to the original budget. Further, time delays behind the original schedule are measured to be on average 20 months.

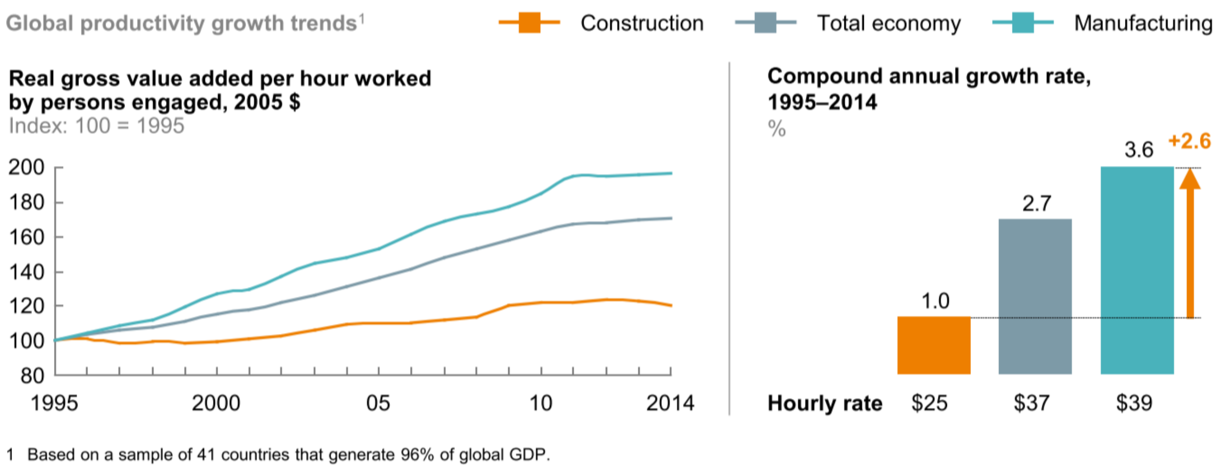


Figure 3: Global productivity growth (Barbosa et al. 2017, p. 12)

Productivity itself, however, is not the only problem the construction industry is facing. In 2018, almost 70,000 workplace injuries have been reported in the British construction industry resulting in overall costs of £15 billion and a delay of 28.2 million working days (Health and Safety Executive 2018). This statistic clearly indicates a general safety issue in the construction industry. Zhou et al. (2013) follow up on this statement, naming the global construction industry "*[…] one of the most dangerous industries with a poor safety record*" (p. 606). This is also supported by the following chart (Figure 4), presenting the fatal injuries to workers by the main industry in Great Britain in 2018 (Health and Safety Executive 2018).

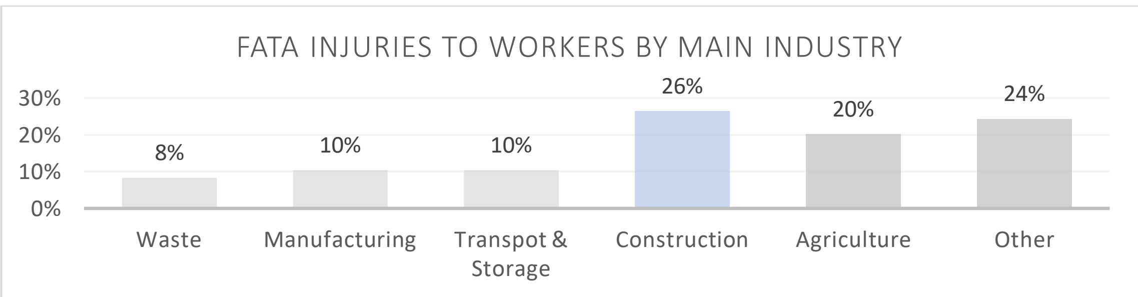


Figure 4: Fatal injuries to workers by the main industry (own visualization)

With 26% of all fatal injuries happening in construction, it is by far the most dangerous industry. Here, Shafique and Rafiq (2019) reveal that most of the fatal accidents, happening in construction are *falling from height*, *striking against or struck by moving object* and *trapped in between objects*. While the first one indicates missing safety barriers, the two latter accident types refer to temporary items on site, that are moved around and interfere with construction workers.

Even though technical improvements and awareness for safety should have reduced workplace injuries in recent decades (e.g Kim et al. (2016b)), there are still safety issues present and even emerging in construction. For example, the US construction industry revealed an increase in fatalities from 2011 to 2015 of 27%, while, all other industries only showed an increase of 3% (Vandermey 2017). Moreover, the rate of fatalities in the US construction industry is with approx. 275% higher than all other industries combined, resulting in enormous costs of construction injuries of many billions of dollars (Ratay 2012). Hence, next to productivity, safety remains a big issue in construction and must be addressed in this thesis. Both poor productivity and safety issues can be summarized as performance issues that need to be improved in order to catch up with other industries.

This general trend of poor construction performance is not expected to be improved without drastic changes in how the industry operates. The reason for that is based on several elemental root causes, which must be addressed and solved in a comprehensive and sustainable manner. Divided into two categories, the industry is suffering from external forces and internal challenges, comprising the industry's dynamic and operational factors at company level. External forces can emerge from different perspectives such as resource shortages, political disturbance, or corruption (Navarro-Astor Elena et al. 2010; Damoah and Kumi 2018), yet, McKinsey identified increasing project and site complexity as one of the most challenging problems (Barbosa et al. 2017). Other reports, however, set the focus more towards internal challenges and the industry's unique characteristics as the root cause for the current situation (Farmer and Branson 2016; World Economic Forum 2016). Often, these differences are used to explain the industry's current situation and its failure to improve. According to Farmer and Branson (2016), especially the high fragmentation of key stakeholders and the project-based nature with on-site production largely impacts the productivity rate. Moreover, the industry's dynamic is placed in a unique and conservative environment as well as a complex client relationship which makes it difficult to make disruptive changes towards the digital transformation. Lastly, weak project monitoring and lack of collaboration within the supply chain are named as causes within the stakeholder operation (Barbosa et al. 2017).

As a result of these characteristics, the industry is highly underdeveloped. Research and Development (R&D) is defined as *"the lifeblood of any industry […]"* (World Economic Forum 2016, p. 14), leveraging an industry to constantly improve and keep up the performance. Thus, investing in innovation and adopting new technology is an essential responsibility every industry must fulfil in order to survive. Yet, the importance of attention towards R&D is exactly what the construction industry has always neglected and is now experiencing the consequences. It is not surprising that the statement that buildings are built the same way as 50 years ago is commonly taken as fact when describing the construction industry (World Economic Forum 2016).
Figure 5 summarizes the identified root problems of the industry and serves as a gateway towards the exploration of more specific problems within the application of this research project.

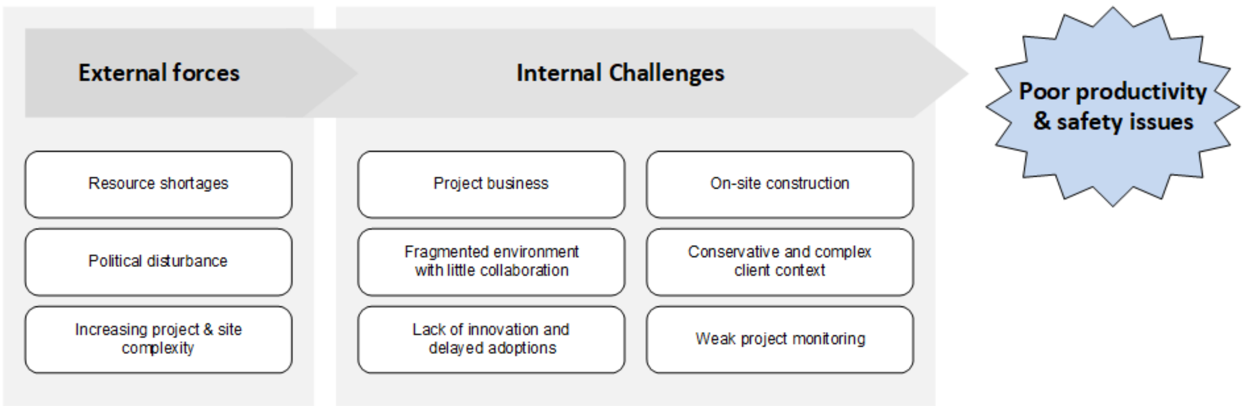


Figure 5: Root causes for productivity and safety issues in construction (own visualization)

Poorly implemented information technology in construction

Referring to the development of other industries, the author explained that the construction industry is far behind the benchmark. Especially in terms of the adoption of information technology (IT), the gap to other industries is huge (Ratajczak et al. 2019). The technological management of IT, however, is determined as one of the main drivers for the crucial digital transformation which must happen in all branches of the industry (Aouad et al. 1999). Recently, there has been an effort in implementing Building Information Modelling (BIM) as the main trend to drive digital transformation within the construction industry and the potential of this new ideology cannot be overestimated (Farmer and Branson 2016).

BIM as a tool is known for its information management capability, improving the entire process of construction, from the early planning until the operation of a building. Nonetheless, the adoption of BIM, as well as correlated IT-technologies, has explicitly experienced great attention in the design and engineering phases. Integration in the construction process has been neglected for various reasons, such as the fragmented and conservative stakeholder environment or the complexities and variances of a construction project on site (Wang and Chong 2015). Ratajczak et al. (2019) agree on the point that the reason for little IT utilization is based on several organizational and technical barriers, e.g. the habitual resistance to change and missing education. Bråthen and Moum (2016) furthermore mention that the industry's root causes are responsible for the delayed adoption of BIM and a lack of appropriate tools to use BIM on site.
Overall, these reasons have created an increasing imbalance of BIM adoption in the industry. Hence, this performance gap in the transition phase between design and construction impacts the benefits of using BIM as it is noted that BIM's full potential can only be achieved if the information is used continuously during all project stages and the model is concurrently updated with accurate and reliable information, extracted from the project site (Chen and Lu (2019); Davies and Harty (2013)). Hence, moving the focus towards the construction site has big potential to improve the output of construction projects by applying information technology.

Construction planning does not reflect the construction process

Partly caused by this poor application of IT-solutions and the still outstanding digital transformation, the construction industry is facing a major image loss due to frequent cost and time overruns. Clients almost expect that the initial budget will be exceeded and actual performance on site does not mirror the planned schedule and estimations (Farmer and Branson 2016). Due to the fragmented environment, the integration of construction expertise from contractors is rarely included in the planning effort (The American Institute of Architects 2007). Therefore, a lot of planning is based on rough estimation from designers, who cannot accurately capture all constraints on site. In this regard, Koseoglu and Nurtan-Gunes (2018) investigated the need for using BIM in construction in order to integrate information from the construction site and update what is planned. A key area, where BIM application is rarely implemented is the site and logistics management, although the potential and synergies are obvious.

Whitlock et al. (2018) even identify that "*poor logistics management is one of the critical factors that affect the performance on construction projects*" (p. 48). Both BIM and construction logistics management are aiming to deliver the right resources to the right people, at the right time, where the resources can either be information or construction items (Whitlock et al. 2018). Thus, BIM-based active management of resources in a construction site can have measurable positive effects on performance.

Yet, this finding is not limited to the application of BIM but can be associated with any technology which is enabling a bilateral information flow between the plan and the actual execution. Especially regarding resource and performance management, the potential of receiving regularly updated information and distributing it to relevant stakeholders has great potential. Hereby, the main benefit is "*[...] having access to real-time information that is automatically updated [...] from [the] construction site*" (Koseoglu and Nurtan-Gunes 2018, p. 1312). Comprehensive real-time tracking of the production process is already a common practice in manufacturing, where data are collected and analysed automatically. Among other benefits, this allows to quickly identify root causes of an occurring problem and implement accurate remedies. According to the World Economic Forum (2016), this practice would also benefit the construction industry by enabling a strong project monitoring, e.g. for construction resources and progress. In this context, Dave et al. (2010) state the productivity and reliability of construction processes are highly affected by the accurate and timely information availability on site. Another benefit of tracking site processes is the relative increase of safety as identified by Zhou et al. (2013). Their research output finds a positive correlation in monitoring construction items and improving safety management.

Bringing this idea towards a broader perspective, applying new technology alone does not holistically improve the construction process, as the implementation of isolated solutions can also lead to information inconsistency, causing errors and rework (Xu et al. 2018). Thus, a crucial part of developing a functioning solution should guarantee interoperability and collaboration between BIM-based management tools and monitoring technology to exchange information and allow a continuous information flow (Ratajczak et al. 2019). Altogether, the missing integration of BIM-based management, IT, and site monitoring with a bilateral information flow between design and construction can be identified as a major issue, damaging construction's global image. On the other hand, this idea also serves as a promising potential to improve construction.

Lack of attention and information regarding temporary construction items (TCIs)

The goal to implement BIM on site can be approached from many different perspectives, as introduced by Koseoglu and Nurtan-Gunes (2018) and Wang and Chong (2015). As one area that is generally overlooked and yet comprises a huge potential for improving construction with the integration in BIM, Kim et al. (2018) inform that proper planning and management of temporary construction items (TCIs) highly affect the project regarding productivity and safety. Hence, focusing the research on this application area may have a significant influence on improving performance in the construction industry in general (Teizer 2015). Narrowing down the problem space to a specific area, furthermore, helps to later define the research scope.

TCIs, comprising items as scaffolding, formwork, supporting struts and safety barriers as well as tools and machines, only receive minor attention in academic research as well as in building planning and management processes (Kim et al. 2016a). There is a big potential to reduce waste, costs, and safety hazards by planning and managing these items. Nowadays, these items are just considered as a percentage of the whole project, cost-wise, and are barely included in planning outputs such as estimations and schedules (Wu et al. 2018). Hence, this common practice is making TCIs a risk factor for productivity and safety on a construction site. Actual information about the utilization and spatiotemporal properties of temporary items, however, would not only enable to reduce resulting economic losses but also the number of accidents on site (Kim et al. 2018).

Reflecting on the identified problem space, productivity and safety present two main issues in the construction industry. Investigating these issues, a more detailed problem space was identified, comprising the poorly implemented information technology and the fact that construction planning does not reflect the construction process. Lastly, this problem space was narrowed down to a specific application area, leading to the following problem definition:

Problem Definition:

"Today's construction industry is suffering from productivity and safety issues due to a lack of BIM and IT integration in construction processes, especially regarding temporary construction items (TCIs)"

2.1.2 Solution Space

In this chapter, the solution space is explored and narrowed down towards a specific solution, aiming to solve the identified problems. To clarify this approach, figure 6 summarizes the main findings of the problem space and provides an outlook towards the solution space.

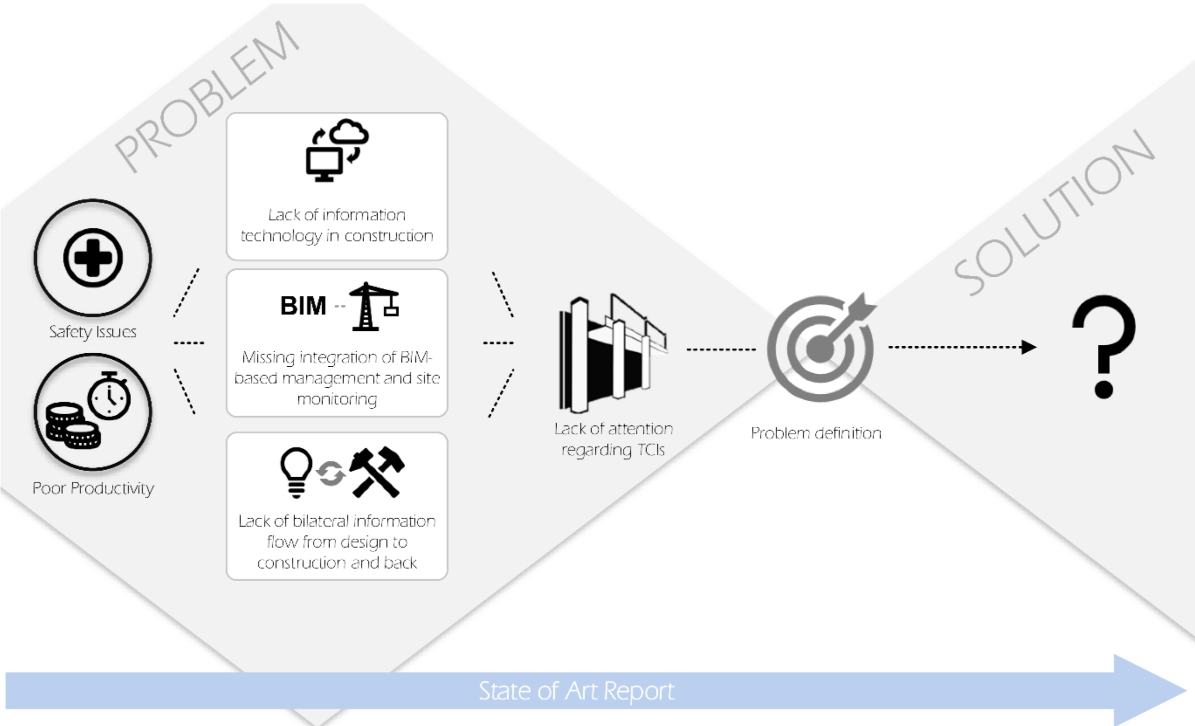


Figure 6: Summary of identified problem space (own visualization)

In the previous part of the state of art report, a narrowed down **problem definition** was created after identifying major shortcomings and problems in the construction industry. The following paragraphs will follow up on the double diamond approach (Heffernan 2017), exploring the solution space according to the defined problem.

Linking the solution analysis back to the problem identification, two areas (external forces and internal challenges) were determined by McKinsey from which the construction industry is suffering (Barbosa et al. 2017). In addition, Barbosa et al. (2017) explored improvement areas, which can be linked to the identified problems. By quantifying their productivity impact and cost-saving potential, Barbosa et al. (2017) provide further information to decide upon the relevance of each improvement area. The following table reveals the link between both papers, providing a starting point for analysing the solution space.

Area	Improvement areas		Impact on productivity (%)	Cost Savings (%)
External Forces	1	Regulation	Enabler	-
Industry Dynamics	2	Collaboration and Contracting	8-9	6-7
	3	Design and Engineering	8-10	7-10
Operation Factors at Company Level	4	Procurement and Supply-Chain Management	7-8	3-5
	5	On-site Execution	6-10	4-5
	6	Technology	14-15	4-6
	7	Capability building	5-7	3-5

Table 1: Improvement areas linked to defined problem space (Barbosa et al. 2017)

As highlighted in blue in table 1, the defined problem space correlates directly with improvement areas five and six (on-site execution and technology), resulting in a productivity increase of up to 25% as well as cost savings of up to 11%. Another consideration might be that in order to get updated information about TCIs, they have to be planned first in order to compare the real progress with what is planned. As it also touches upon the aspect of integrating and digitizing supply-chain workflows, the overall impact might increase further with the improvement areas three and four (Barbosa et al. 2017). Similarly interesting is that the selected improvement areas mainly address means at company level, meaning that the derived solutions can be implemented by each company and are not dependent on major industry changes. Following this train of thought, the next sections will explore and highlight different solutions in literature that are derived from the selected improvement areas four to six. To provide a solution frame, the selected improvement areas are described beforehand.

Improvement area 5 - *On-site Execution* - addresses the need to improve transparency and project management in construction by efficiently monitoring what has been planned. Furthermore, it is recommended to use KPI's for performance and progress monitoring of the construction site.

Improvement area 6 – *Technology* - gives a general recommendation to increase the use and investment of digital technology and IT in the construction industry. Examples are the use of BIM throughout the entire construction project, advanced tools for on-site monitoring of productivity and progress in real-time as well as digital collaboration platforms for data flow and rapid information exchange for all relevant stakeholders. Moreover, Barbosa et al. (2017) mention that the implementation of automatic site monitoring can increase productivity for up to 50%.

As mentioned earlier, improvement areas three and four might also be relevant for the solution exploration. As the other two improvement areas are both aiming to digitalize construction, both the design phase and the supply chain should be considered as well to avoid the creation of silos and isolated solutions.

Going further, the following sections will explore potential solutions from literature that fit the defined improvement areas.

Adoption of BIM and consideration of TCIs for site and logistics management in construction

The need to adopt and integrate BIM at the construction site has often been mentioned in current literature (Koseoglu and Nurtan-Gunes 2018; Davies and Harty 2013; Whitlock et al. 2018). Concerning temporary construction, the focus is on both site and logistics management where BIM-data can be used to improve and control construction workflows. In this aspect, the bilateral information flow from planning to execution and backwards is considered to be the main objective for bringing BIM on site (Chen and Lu 2019).

Whitlock et al. (2018) investigate the adoption of BIM for construction logistics management (CLM), highlight advantages and barriers to it and provide recommendations for further research. The research first identifies the scope of CLM, involving "*[…] strategic storage, handling, transportation and distribution of resources, as well as planning of a building site's layout […]*" (Whitlock et al. 2018, p. 48). Furthermore, CLM accounts for a continuous and lean flow of material and equipment, a lean storage approach and dynamic building processes regarding space and time on site. This counts both for permanent construction items (PCIs) and TCIs. For the latter, it is identified that BIM-based 4D simulations have the most beneficial impact. This allows the project manager to analyse the construction process and progress over time. Among other benefits, analysing construction processes with 4D-BIM improves the understanding of logistics on site which also increases safety (Sulankivi et al. 2009). According to Whitlock et al. (2018), it is not enough to establish a static site plan before construction starts. A crucial step during construction is the continuous review and adjustment of the 4D site plan as well as the BIM-model with updated information from the construction site in order to reduce conflicts and boost site efficiency. Besides updating the model and the plan according to the construction progress, CLM will also benefit by integrating expert information from special contractors and trades on site.

This involvement does not only improve the understanding of the logistic process of each representative trade but also allows to collaboratively identify problems and propose solutions within the project team (Ballard et al. 2007). In conclusion, the regarded research proposes the utilization of 4D BIM logistics models to coordinate and control logistics processes as well as a stakeholder integration for proper information exchange of common data.

Lean Construction & Last Planner System (LPS)

Guerriero et al. (2017) continue with the idea of using 4D BIM in order to improve construction processes, based on lean principles. To do so, the paper proposes the Smart Construction Planner® (SCP), an integrated and digital tool that includes both aspects of 4D BIM use cases and lean construction principles. Firstly, SCP utilizes the benefit of combining 4D BIM with site management and proposes a dynamic site layout planning which is able to track material flow and constantly adapts to the current state of the construction site. The paper names efficient material storage and continuous construction flow as the benefits of this planning approach.
Secondly, SCP addresses scheduling and aims to integrate the Last Planner® System into a 4D model. LPS is based on lean construction principles and enables a systematic as well as continuous production control with all construction trades involved, aiming at improving the reliability of construction planning and thus, improving site performance (Ballard et al. 2007). In order to complete the scheduling task, location-based planning and a collaborative approach are considered as well. This shall create a comprehensive and lean scheduling approach that provides useful data. The use of these data can be further extended towards the construction process by monitoring the work progress and updating the 4D model. Hence, the third benefit is identified to be monitoring of construction processes. Lastly, Guerriero et al. (2017) mention the general advantage of 4D to visualize construction for a better communication on a construction project.
The Smart Construction Planner® is a solution that leverages the integration of BIM (4D BIM) with other approaches, mainly from lean construction. It provides a wide application range from design to construction, involving among other uses, scheduling, site layout, monitoring, and visualization, and with that, expresses its relevance for this research.

Site-BIM is the next solution this chapter will highlight. This technology brings BIM data to the construction site, to the benefit of the workers who can return with their feedback, and updated progress details. Davies and Harty (2013) first introduced the new technology on a case study, where "Site-BIM" was implemented in a large hospital project. Koseoglu and Nurtan-Gunes (2018) continued the research with the implementation of the mobile BIM solution on a complex airport project. In relation to the **problem definition**, the following two out of five aspects of the mobile BIM application are highlighted. The first one is resource management in which BIM is used to track progress and resources on site. Crew members can easily communicate resource issues (crew, material, or site logistics) via their iPad and the BIM application automatically creates a task for the relevant contractor to fix the issue. To increase transparency, the problem information is automatically visualized in a dashboard, accessible for all needed stakeholders.

Process management is the next aspect of the mobile BIM application which is considered useful for this research, due to its performance monitoring ability. Site workers can utilize the application to track their work progress and with the generated information, automatically create a performance report for each trade. Project managers can hence benefit from real-time information from the site enhancing their decision-making process. Furthermore, the related information is made available also for the different construction disciplines which by that, receive regular updates about the projects and their progress. In general, the approach to integrate BIM into construction site processes brings many advantages regarding a facilitated information flow. However, especially the practical implementation of resource and performance management bears challenges in large and complex projects. Here, the biggest challenge is to integrate all resources and performance information from all disciplines on the construction site into one platform, as the fragmented industry limits collaboration. As presented in the problem space section, TCIs are often not part of this consideration. Hence, TCIs must be integrated into BIM-planning before their data can be utilized for improving the site and logistics management.

Similar to "Site-BIM", Chen and Lu (2019) argue that only by integrating BIM within the construction processes, its full potential can be achieved. "*Bridging BIM and building (BBB)*" *(Chen and Lu 2019, p. 1518)* therefore, stands for a continuous updating of the BIM model, using real-time and reliable project information and automatic information sharing for the relevant stakeholders.

In order to make this happen, increasing automation in collecting and processing information is recommended, followed by a visualization and sharing of the newly gained information in response to the stakeholders' needs. Hence, a cloud-based platform for information management is a crucial part of improving construction as it enables bilateral information flow between BIM and the construction site. The availability of the information had a positive effect on saving time and buffers could be determined more accurately to ensure continuous construction progress.

Site monitoring using IoT-technology and integration of BIM data

The previous paragraphs mainly informed about the state of art solutions regarding BIM integration in construction processes, where all solutions emphasized the application of site monitoring as part of the process. Yet, most of the solutions (Whitlock et al. 2018; Davies and Harty 2013) still drew upon manual work to retrieve information from the construction site and only the BBB solution touched upon the utilization of IoT-technology for automatic information retrieval (Chen and Lu 2019). According to Zhou et al. (2013), site monitoring using advanced technologies is a trend in the construction industry for productivity and safety monitoring. In existing literature, different types of technology are applied to receive, transmit as well as visualize the information. These technologies include ICT-technology, sensor-based technology, and virtual reality. However, most of these technology applications were limited to academic research and there is a general need in the industry to put research into practice. Thus, the following paragraphs will focus on solutions that were already tested in either case studies or pilot projects and use advanced technologies to enable improved site monitoring with automatic real-time tracking of construction processes.

Similar to BBB, Xu et al. (2018) and Ko et al. (2016) explored the use of a cloud platform to enable real-time tracking of prefabrication processes. The focus of these studies, however, is less the application of BIM, but rather an exploitation of IoT-technology and cloud assets, especially regarding the implementation in Small and Medium Enterprises (SMEs). In particular, radio frequency identification (RFID), global positioning system (GPS), and ultra-wideband are named as promising tracking technologies to be integrated into the process. Here, the platform consists of a comprehensive cloud asset data model which is characterized by its compatibility to be applied on different physical assets.

Ko et al. (2016) provide a prototype solution for tracking construction materials within the entire supply chain using RFID technology. The approach of Xu et al. (2018) is based on this prototype but differs in its specific application. Ko et al. (2016) provide a general solution to track construction material in batches without the need to specify each item. In contrast, Xu et al. (2018) focus on unique prefabrication items which require instance-level integration and data collection. Moreover, as other solutions have already mentioned, both papers address the need to integrate the building model with all required resources into the monitoring system and base decision-making as well as collaboration among all involved stakeholders on the building model. Regarding TCIs, this means that information of these items needs to be included in the data environment between planning and construction.

One aspect that is missing in the proposed solutions is the integration of specific location data of the tracked items on site, especially when dealing with items that frequently change their location and are reused many times during the project (Beale and André 2017). An interesting reference, integrating both RFID real-time tracking of construction items as well as the location-based management system (LBMS), is a master thesis from Aalborg University, written by Nielsen (2016). This research study combines RFID-tracking and location-based planning within the BIM-environment to locate tagged items and in this context also to ensure that the right items are used in the right locations and are delivered at the right time. Nielsen (2016) developed a functioning system, connecting RFID codes and GUID codes which are used in BIM applications to identify instance resources. Therefore, he argues that there is a need to develop an application programming interface (API) that can handle the information and communicate with the system, using the predefined identification codes. Especially when linking information from different BIM applications, an interoperable unique identifier is critical to ensure the quality of the data. On a construction site, the main benefit was identified to be the real-time knowledge about where specific material is stored which saves a lot of time. Automatic registration and documentation of tagged resources are further mentioned as site benefits. In general, real-time tracking and mapping of construction items will lead to a leaner and more reliable planning and management process. It is stated that there is a big potential to reduce waste and cost by having real-time information about these items and sharing this information with the relevant stakeholders.

The conceptual logistics management process and communication system is presented as a reference below (Figure 7).

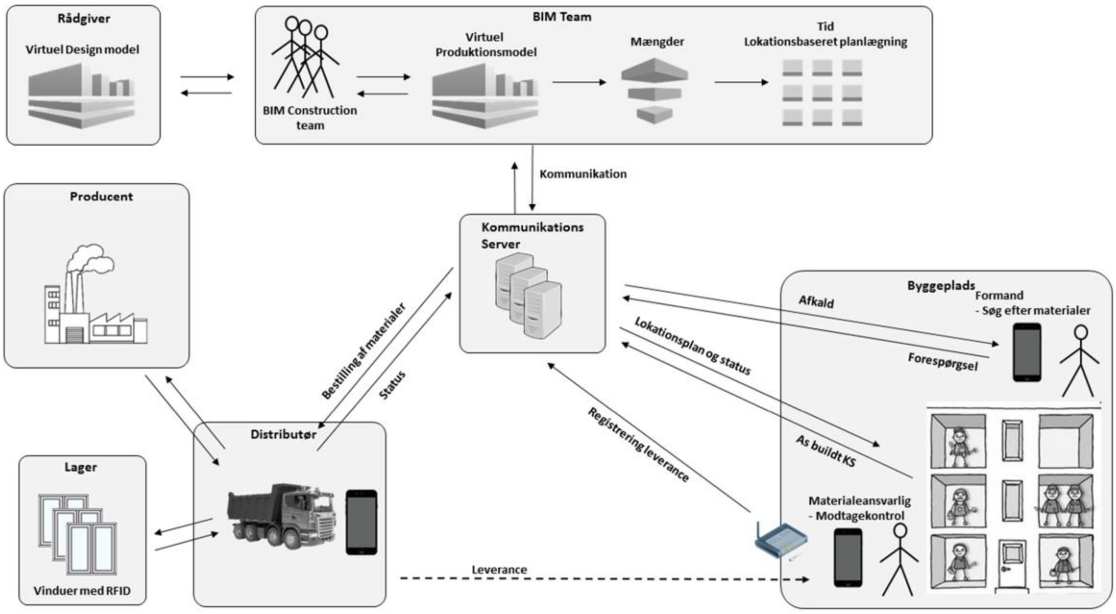


Figure 7: Logistics management process using RFID and LBMS (Nielsen 2016, p. 12)

Apart from the presented studies, there are several other papers in literature, investigating the use of IoT-technology for material handling in the construction industry. Yet, most of them solely put their focus on the utilization of RFID-tags (Nielsen 2016; Xu et al. 2018; Fang et al. 2016; Ko et al. 2016). Other solutions are either error-prone and not flexible enough as QR-codes (Lorenzo et al. 2014) or are not applicable to tag physical items because they require a mobile device to be tracked as with the use of Bluetooth Low Energy (BLE) beacons/ sensors (Park et al. 2016). Moreover, most conducted research within the construction industry, addressing the use of IoT, is focused either on tracking workers or prefabricated materials, but there is a lack of research for TCIs. Therefore, the potential of IoT for tracking TCIs on a construction site will be further taken into consideration in the subsequent sections of this paper.

Automated dashboard visualization of real-time information

Gathering information from planning and monitoring of resources can give a great amount and quality of data. However, to add value to the project, the gained data needs to be sorted and translated for the relevant stakeholders, who draw upon the data to improve their processes.
Ideally, this should happen without the need of the stakeholder to interfere in the process of translating tracked data into useful knowledge. Construction managers, for example, cannot focus on important tasks because 30-50% of their time is spent on collecting and analysing data from the construction site when using manual tools (McCulloch 1997). Hence, an automated process of presenting data the way it benefits each stakeholder is needed, resulting in a tailor-made presentation for all relevant project members (Ratajczak et al. 2018).
Based on these requirements, Ratajczak et al. (2018) developed an interactive and web-based dashboard application for performance monitoring. The dashboard presents different KPIs from the construction site which are customized to the specific users, providing tailored insights into the construction progress to foster proper decision making. The dashboard in this example consists of a 3D BIM viewer of the project, a section with tailored information for the selected user level (tier) of the project as well as graphs that represent KPI trends. Hereby, the dashboard's structure is aligned with the location breakdown structure in the construction project in order to plan and monitor location-based tasks more efficiently. On this basis, the dashboard covers four different user levels or tiers, enabling a tailored and simple data presentation of construction processes. Tier 0 represents the building level and serves as an information source for the higher-level stakeholders as the client, company manager, or project supervisor. KPI's like PPC (Planned Percent Complete) or project progress are used to give a general update on the project status. Tier 1 contains the construction work packages, providing more detailed information about the progress of each work package, and serving the project managers. Going one step higher on the tiered structure, Tier 2 provides the site manager with updated information on each construction task in order to plan and monitor construction on a daily basis. The last tier (Tier 3) is supporting the foremen of each trade with real-time data of every single construction activity, needed to complete a construction task. An example could be the activity sequence of reinforcement, formwork, concrete pouring, stripping, and post-treatment in order to complete the construction task of erecting an in-situ concrete wall.

In this specific case, the data are collected by the foreman, typing in progress information manually in a mobile app that automatically communicates with the dashboard. How this dashboard solution can add value to this research will be explored the solution development in chapter 6, by investigating the dashboard requirements and the use of specific KPI's. However, this paper clearly reveals the importance of establishing an automated dashboard application that is able to merge real-time information, BIM, and lean functionalities in order to maximize the added value of construction resource tracking. Furthermore, it recommends a collaborative approach that includes all relevant stakeholders in the utilization of the gained knowledge. Following up on this recommendation, the next paragraph provides insights into the state of art research regarding collaborative and lean methods to improve construction processes.

Integration of lean principles and collaboration aspects

The integration of the supply chain in site monitoring activities has been addressed by two research papers that introduced a system to track prefabricated construction items (Nielsen 2016; Xu et al. 2018). For temporary construction, this approach could be beneficial as well when integrating the equipment providers which are usually renting out the items for construction sites. By doing that, project managers receive more accurate and almost real-time information for their decision making (Turkan et al. 2014).

Furthermore, the whole implementation of a transparent material handling system should benefit all relevant stakeholders for their decision making in order to add comprehensive value to the entire construction project and improve collaboration (Rischmoller et al. 2018). Therefore, a functioning information exchange must be an essential part of such a system. Primarily, this can be done by developing an automated dashboard that provides tailored information for each stakeholder, as introduced before. However, to foster collaboration on the construction site, it might be beneficial to combine the KPI-based dashboard information with LPS-planning principles in order to provide all construction trades with new information. Integrating the supply chain and construction companies more closely would enable a Lean Construction-based pull approach for resource management and improve the coordination of logistics with a better planning and faster information exchange (Guerriero et al. 2017).

Hence, early integration of all relevant stakeholders to the project and collaborative information exchange is a key for improving construction logistics management.

In conclusion, the reviewed state of art solutions from literature are providing a potent knowledge base for further investigation within the scope of the defined problem. In order to provide an overview, figure 8 is summarizing the new findings.

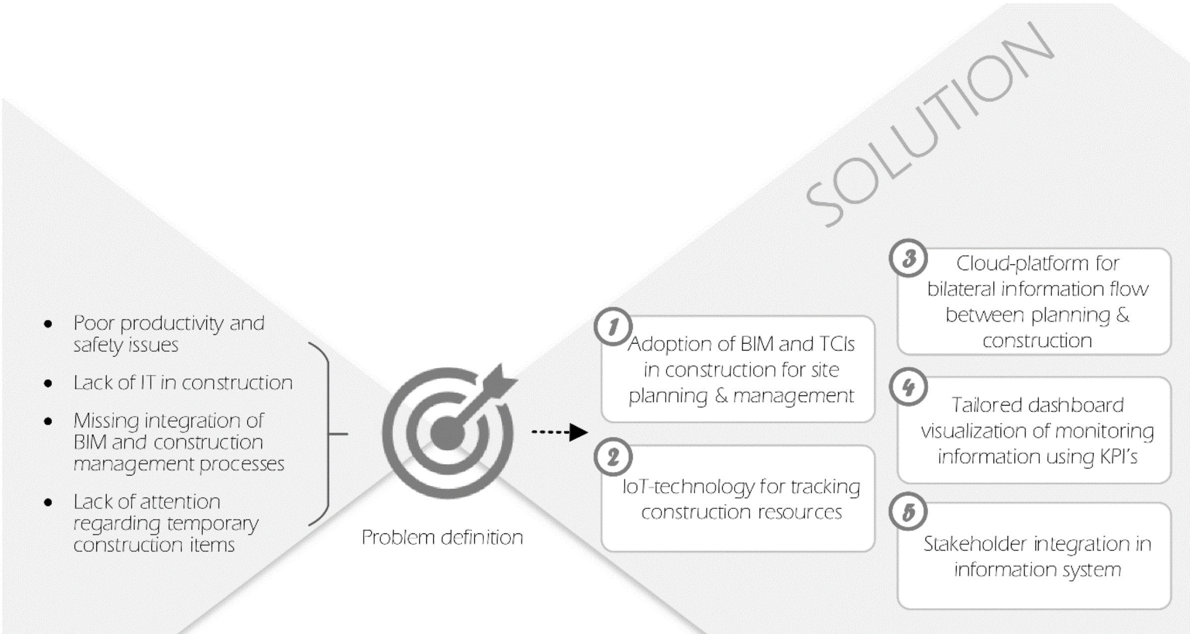


Figure 8: Findings from state of art solutions from the literature review (own visualization)

As a result of the literature review, the following compilation of five existing solutions are recommended to be implemented for solving the determined problem space and thus, are identified to be relevant to the further development of this thesis.

1) Adoption of BIM and TCIs consideration in construction for site management
2) IoT-technology for tracking construction resources
3) Cloud-based platform for bilateral information flow between planning & construction
4) Tailored dashboard visualization of monitoring information using KPI's
5) Stakeholder integration in information system

Yet, the presented solutions cannot give a comprehensive recommendation as they only cover the academic perspective of the state of art in construction. Thus, a practical point of view shall be applied as well to verify assumptions from literature, before eventually framing the problem and solution space for this research in chapter 3.

2.2 Practical Point of View

As described above, the practical point of view is supposed to validate the findings from the previous chapter to substantiate their relevance and importance. Therefore, two interviews with Danish construction experts were conducted to further explore the identified problem and solution space from a practical point of view, supporting the framing of the research objective.

The qualitative interviews were conducted in a semi-structured approach, based on Kvale (1996), are aligned to the theoretical state of art review and accompanied by a customized interview guide (**Appendix 5.1**). On the one hand, the interview guide refers to the problem space and tries to extract the interviewee's opinion about the identified **problem definition**. On the other hand, it covers the solution space, asking for the professional opinion of the interviewees about the derived solutions. This helps to narrow down the solution space towards a specific research case that is most relevant both in theory and practice. The answers to each question can be found in **Appendix 6.1**.

Before elaborating on a discussion about the findings of the interviews, the following table introduces the interviewees and their professional backgrounds.

<table>
<tr><th>A</th><th colspan="2">Introduction to Interviewees (Group A) – Verifying Literature Findings</th><th>Experience</th></tr>
<tr><td rowspan="2">1</td><td>Consultant 1</td><td>Client Advisor at Exigo A/S</td><td>+ 5 years</td></tr>
<tr><td>Value-added</td><td colspan="2">• Project management with focus on data-driven solutions
• Responsible for the implementation of new solutions in projects
• Knowledge about current & future use of technology in construction</td></tr>
<tr><td rowspan="2">2</td><td>Consultant 2</td><td>Head of Digitalization at Consultancy A</td><td>+ 15 years</td></tr>
<tr><td>Value-added</td><td colspan="2">• Implementation of productivity-enhancing tools for construction
• Knowledge about current & future use of technology in construction
• Project leader of numerous VDC projects</td></tr>
</table>

Table 2: Introduction to Interviewee Group A

Starting with the problem space, both interview partners strongly agreed that the conservative industry mentality and lack of innovation are the main drivers causing productivity and safety issues on a construction site. Furthermore, Consultant 2 informed that construction logistics are a general problem due to the increasing complexity and decreasing storage space of the construction sites.

Construction is a dynamic production and as resources are moved around constantly, dynamic planning of a construction site is needed to ensure a continuous flow of construction activities. Dynamic and proper site plans are technically feasible but in practice, there is either a lack of attention or in case a site plan is created, it is based on unproven assumptions. In this regard, Consultant 1 experienced that site layouts, created by designers are only based on theory and lacks site experience. Therefore, a knowledge transfer of site experience needs to be enabled and integrated into the planning phase. According to Consultant 2, a general problem in construction is that planning of construction logistics and the site layout is underprioritized and therefore, poorly planned. This leads to a lack of information for the construction management regarding the procurement schedule and inventory on site.

As contractors and subcontractors handle the construction site with a day-to-day problem-solving mentality and "*[…] are not looking far enough ahead to have that degree of planning that we need*" (Consultant 2, 11.03.2020), poor productivity as well as safety issues are experienced on site. Consultant 1 agreed and stated that the problem concerns the construction professionals, e.g. site or construction manager. They manage the site based on their experience as they always did without a master plan to follow. In this case, this valuable knowledge stays within one person and blocks the information flow in a project because nothing is documented. Consultant 1 identified this as a critical risk factor which has to be solved and mentioned: "*I'm scared if a guy like that leaves or gets sick for a week. That's the real problem*" (Consultant 1, 19.02.2020). Therefore, both interviewees highly recommend the use of IT for planning, documenting, automating, and monitoring of construction activities.

With regard to TCIs, both interviews revealed that current construction comprises a lack of information regarding TCIs in logistics management. This lack of attention is even more obvious than for other site layout considerations. Although the need for planning and monitoring these components on site to reduce costs and waste is well-known, TCIs are often not planned at all and their costs are only considered as a percentage of the total construction costs. Furthermore, TCIs are ordered on an assumption of the construction manager and then deposited on site without detailed information when what types, and how many items are used in which location of the project. There is no look-ahead vision and lean management of TCIs is far from being applicable.

According to Consultant 1, the management of TCIs, as other site management tasks, is an iterative approach from day to day. To overcome this behaviour, Consultant 1 explained that the easiest way to consider TCIs is to create a link to what is already part of the construction planning. By linking them to respective permanent building parts and the established schedule, TCI consideration would happen in a passive way and monitoring would be enabled by the progress tracking of the permanent building parts. An in-situ concrete wall with certain properties, for example, requires a certain amount and type of formwork, supporting structures, and working platforms. In a specific height, scaffolding might be needed as well. Consultant 1 also mentioned that this relation can be established a long time before construction starts. First, generically based on experience and data from the contractor and the supplier and then with specific geometry and properties from the BIM model. In this regard, Consultant 2 explained that automatic and rule-based planning of TCIs can be deduced from a BIM-model, based on geometry. By developing an algorithm that can automatically quantify the required amount and type of standard TCIs, the process of planning TCIs is transformed from being manual and error-prone to an automatic and efficient approach that can be integrated early in a construction project. Initially, TCIs can be planned with generic information of a default set of standard products. After selecting specific TCI products for the construction site, data from the TCI provider can be integrated into the generic logic to align the plan with their work process. This will also enhance the perspective of the subcontractors as their role is crucial to improve construction productivity (Consultant 2 and Loosemore (2014)).

According to Consultant 2, TCIs do no need to be modelled as their geometry is not of primary interest in a 3D model and it is difficult to consider a moving resource in a static model. The most important parameters to consider for the automatic planning of TCIs is how much (quantity), of what type (type of TCI) is needed when (time) and where (location). Besides this information, a picture of the item, its weight, size, and function are identified by Consultant 1 to be important information. Consultant 1 further highlighted that a safety risk factor of each item, based on experience should be included as well. Both interview partners stated that an early consideration and planning of the site and logistic processes regarding TCIs with automated monitoring on site has a high potential to improve construction. In consequence, this also means that tracking TCIs, using IoT-technology, is only possible if data about these items are created beforehand.

Consequently, the information can be transferred to the construction site and monitored to verify progress according to what is planned. However, Consultant 1 added that for a successful and sustainable implementation, the new process must not require major behavioural changes for the construction workers. This emphasizes the importance of automatization as described by Consultant 2. Hence, for the sake of the research objective and relevance, the intention to improve the logistic management process of TCIs must start with the consideration of TCIs in construction site planning in general. Regarding the 5 steps for process improvement, identified in the state of art review, this means that the focus will slightly shift from step 2, IoT-tracking towards step 1, BIM planning as TCIs have to be planned first. Step 2, step 3, the cloud platform, 4, the tailor-made visualization, and step 5, the stakeholder integration, however, are still relevant for the further development of this paper and can be considered in their successive order (Figure 9).

After TCIs are quantified, based on the given BIM-model, and information about their use regarding time and location is established, "*the next step that makes your planning better is to have a better and faster data flow on how your site actually looks and what is going on, on site*" (Consultant 2, 11.03.2020). In other words, a monitoring system of the planned situation with a feedback loop from the construction site towards planning must be created. Confirming this statement, Consultant 1 claimed that, in case the consideration of TCIs in construction is accomplished, indeed, IoT-enabled and automated tracking of TCIs would further improve the process, as the location of specific items can be verified in real-time. Regarding the IoT-solution and in contrast to many research papers, both interview partners claimed that RFID is not a suitable technology for tracking items that are frequently moved around on site and reused several times during the project, as it requires manual scanning of the tags. And unless there is a robot available that can scan all items on a construction site at night, this technology is not suitable, as identified from Consultant 2. Consultant 1 also questioned the relevance of RFID as this technology has been available already for many years but was never fully integrated into the industry. In the opinion of Consultant 1, the new 5G-technology might be the technology fulfilling all requirements to be implemented in the construction. According to Consultant 1, this technology allows to automatically track items on a precise level, only requires a cheap and tiny antenna and furthermore, there is no need for an additional local transmitter or for an active participation of construction workers.

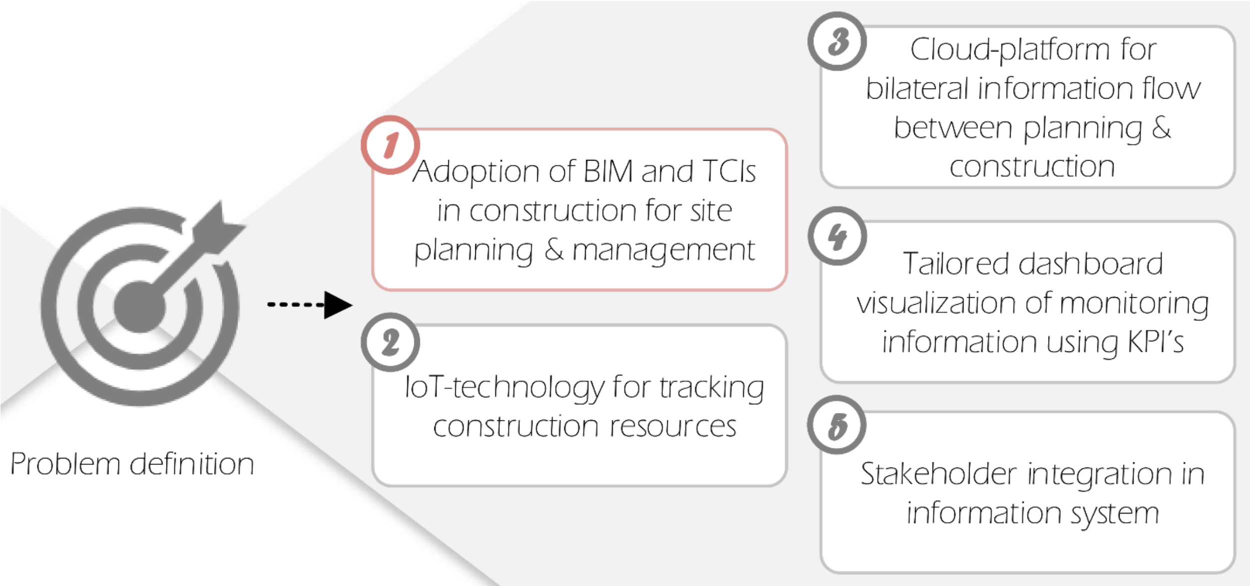


Figure 9: Focus areas of the solution space (Primary focus in red) (own visualization)

Concluding the analysis of the interviews, findings from the literature review are generally confirmed and validated. The focus area on the site & logistics management process of TCIs is considered an important and valid direction and the interviewees agreed on all five recommendations of how this process can be optimized. However, during the interviews, the focus shifted towards the planning of TCIs as the first step in the improvement chain which needs to be established before the other steps can be considered. Therefore, this research mainly focuses on a simple consideration of TCIs in construction planning, resulting in a transparent utilization and integrated information flow.

Although the research scope is set to mainly explore the planning of TCIs, the other steps of the process improvement are still taken into consideration and help to develop a solution to improve productivity and safety on site. Thus, the research aims at developing a flexible solution to which adjustments and further developments can be easily made. However, this is subject to the next chapter, where the specific research scope and objective are derived from the findings of chapter 2.

Chapter 3: Framing Problem & Solution Space

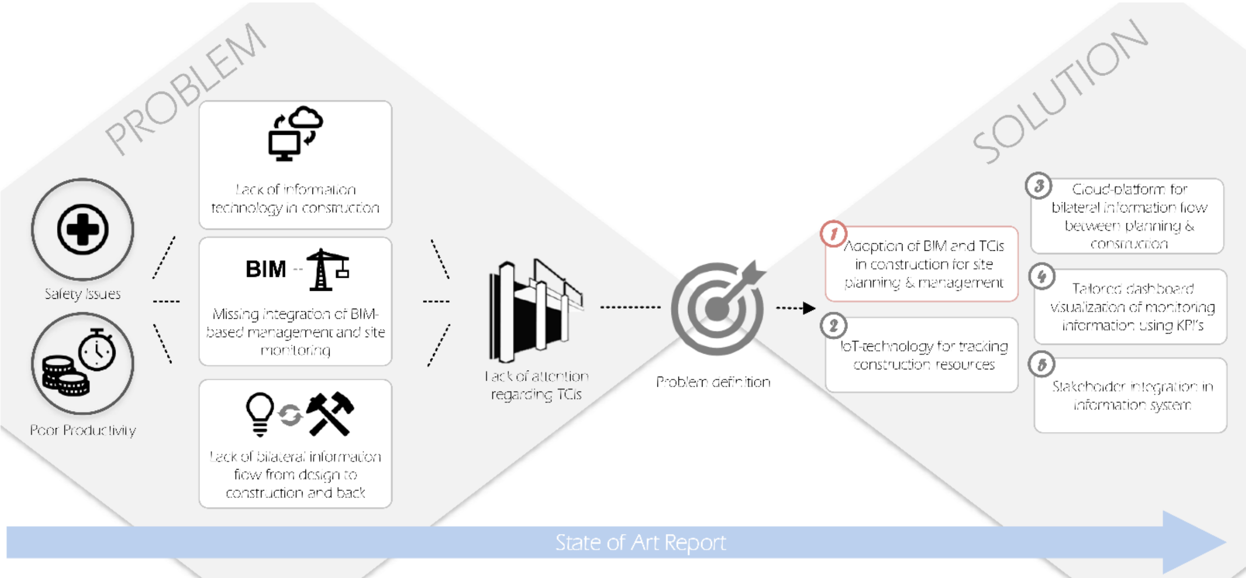


Figure 10: Overview of findings from chapter 2 (own visualization)

The problem space of the state of art review identified a practical problem in the industry regarding productivity and safety on construction sites. This general problem within the scope of site and logistics management motivates the research to answer the following general question.

"How can productivity and safety issues at construction sites be resolved?"

This question arises from the explored problem space and forms the basis of the overall research question, this paper intends to answer. As the state of art review further revealed, existing technologies and methods have the potential to overcome the identified challenges regarding construction. Based on the findings, this research identified a specific problem in the construction industry to base the focus on and derived a holistic framework to solve the problem. This chapter now tries to frame the solution space in order to define the research objective.

The solution analysis in chapter 2 resulted in the following five recommendations that together, if consecutively adopted, form the solution framework to improve productivity and safety in construction by considering TCIs in the construction management process.

1) Adoption of BIM and TCIs consideration in construction for site management
2) IoT-technology for tracking construction resources
3) Cloud-based platform for bilateral information flow between planning & construction

4) Tailored dashboard visualization of monitoring information using KPI's
5) Stakeholder integration in information system

After integrating the practical point of view to the literature analysis, the research scope was narrowed down, focusing mainly on the adoption of BIM and TCI consideration in construction. It is identified that for monitoring TCIs during construction, the items first have to be considered within the planned in the project. If the focus would only be on tracking the items, a reference is missing to compare the tracked data with. Hence, a simple way to plan TCIs in construction management must be developed. An elegant way to do that without modelling each TCI in the 4D-model is to link TCIs to their respective permanent building parts and their schedule and with that, passively plan and monitor the used TCIs on the construction site. In order to accomplish this link, a database needs to be created which holds information about TCIs and their relationship to specific construction activities. This data can then be linked to 4D-BIM data of the construction project as geometry, building objects, schedule, and location, to enable a passive management of TCIs. Additionally, including real-time data about the construction progress would provide updated information about the TCI utilization, allowing to generate a lean management process for better managing TCIs.

The solution framework, described above, forms the research scope of this thesis. Thus, the research's aims at developing an integrated database, comprising TCI information and model as well as schedule data from the BIM-based project delivery to automatically plan TCIs and enable a passive progress monitoring of these items on a construction site. In conclusion, the following **problem definition** and research objective are defined as a result of the state of art review:

Problem Definition:

"Today's construction industry is suffering from productivity and safety issues due to a lack of BIM and IT integration in construction processes, especially regarding temporary construction items (TCIs)"

Research Objective:

"Developing an integrated and lean management process of temporary construction items (TCIs) with a data-driven information flow between planning and construction to improve productivity and safety on site"

The **research objective** constitutes a holistic approach, aiming at first integrating TCIs in a simple way into the BIM-based project delivery and subsequently also addressing further aspects as the use of IoT-sensors for real-time tracking of the TCIs, the integration of the supply chain and tailored information distribution and visualization for all relevant stakeholders. Due to the lack of TCI consideration in theory and practice, this research will form the first step of a novel improvement process, which must be further optimized by consequently implementing the consecutive recommendations 1 to 5. Consequently, the proposed solution shall enable further adjustments and linking of new data to facilitate further improvements.

In order to summarize the results of this chapter, the following framework is conceptually visualizing the process of managing TCIs in a construction project with the consideration of the five recommendations. This process is subject to further detailing in chapter 5 and chapter 6, where each component will be examined individually and in relation to the whole process.

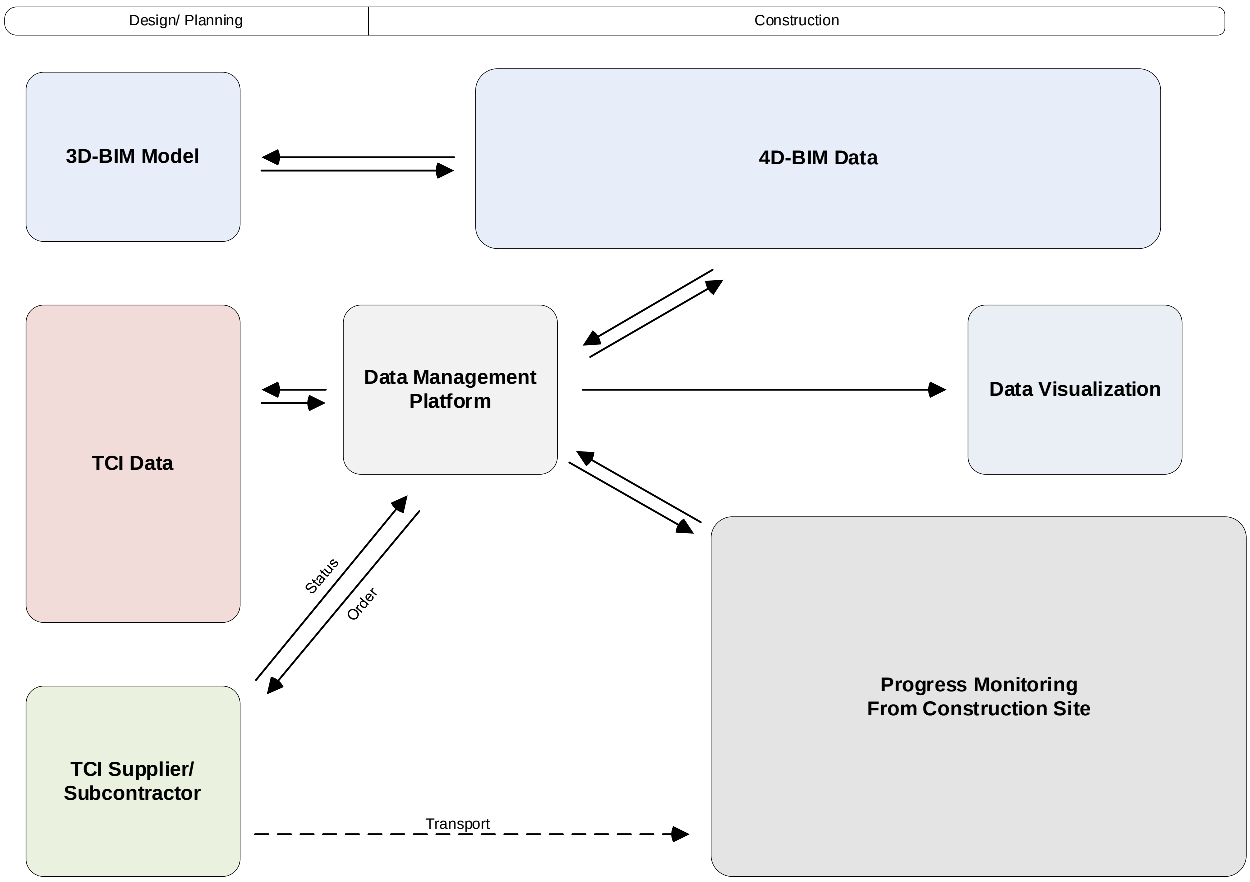


Figure 11: High-level framework of the innovative TCI management (own visualization)

Chapter 4: Research Design & Methodology

The chapter "Research Design & Methodology" aims to classify the research within a scientific frame based on a specific methodology. Adding an academic point of view, this framing allows the research to be guided within a verified structure. Furthermore, the introduction to a generic methodology allows to derive sub-questions that are aligned to an overall research methodology and subsequently explore the different aspects of the main research question. Moreover, developing a clear research design will help the reader to follow the content of this paper.

In this context, Silverman (2009, p. 13) defines methodology as "*a general approach to studying research topics*" and method as "*a specific research technique for attaining some objective*". Differentiating between methodology and method, this chapter first introduces the overall thesis methodology and then proposes methods for exploring and answering the research questions.

4.1 Managing Innovation

Introducing a new approach to consider TCIs in construction site planning and management and by that utilizing new technologies is a task of creating innovation in construction. As a result, productivity and safety shall be increased with the use of the created data. Innovation in its most simple definition means the use of a new idea or to make something new (Cambridge Dictionary 2020). However, more recent literature focuses more on the development aspect of new knowledge, and therefore, innovation is often described as the process of "*growing good ideas into practical use*" (Tidd and Bessant 2012, p. 16).

Regarding the proposed research frame, there is a need for a valid methodology that guides the research through each chapter. While supporting the research project with a general and structured model to develop innovation, such a methodology must also allow to focus on the specific use case of the research by not imposing an exorbitantly strict guideline. Therefore, the methodology *Managing Innovation* (Tidd and Bessant 2012) is chosen as it includes a general process view of managing innovation which can be projected on the research design of this thesis. Hereby, the proposed process model of managing innovation is separated into the four steps, *Search*, *Select*, *Implement* and *Capture*, leading to a successful implementation of innovations in any field of application (Setia Margana 2019).

These steps can be seen as consecutive phases for developing an innovation and cover the entire process from the early need analysis and the identification of triggers until the implementation and value creation of the proposed innovation. Thus, the process model, which is visualized in figure 12 and based on Tidd and Bessant (2012, p. 12), comprises a holistic view for any kind of innovation and is suitable to be utilized as a guiding reference in the use case of this thesis. The following section will introduce the different phases of managing innovation and aims to derive specific questions from the generic model to later define the research questions.

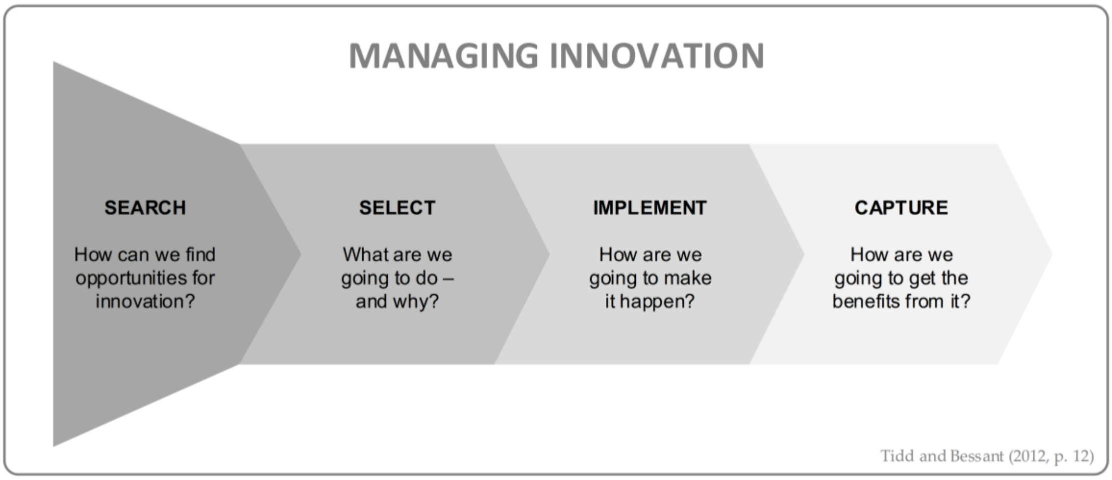


Figure 12: Model of the innovation process (own visualization)

4.1.1 Search (Phase 1)

The first phase in the innovation process model addresses the need for innovation. By identifying signals calling for change, a need analysis within the considered environment can be conducted as a starting point of introducing an innovation. Those signals can emerge from technological opportunities or legal requirements but might also be based on poor performance. In the generic process model, answering the following generic question accomplishes the first step of managing innovation.

Generic: How can we find opportunities for innovation?

Regarding this research, *Search* focuses on detecting current challenges in the construction industry and exploring technological opportunities to overcome these challenges. Hence, the following specific question is derived from the generic model and applied to this use case.

Specific: What are the current problems and potential solutions in the construction industry?

4.1.2 Select (Phase 2)

In phase one, a wide range of signals as problems and new solutions within the construction industry are drawn from the generic definition. Following the process model, these signals must be narrowed down to a specific application. The purpose of this step is to put the focus on a small but relevant use case, in which innovation is needed. Here, the selection must fit well with the applicant's competence and strategy as a misfit often results in innovation failure (Cooper 2008).

Generic: What are we going to do and why?

As identified in chapter 2 and 3, the most relevant use case is the consideration of TCIs in construction management to improve the site and logistics management by enabling a lean management of those items. As deduced from the interview findings in chapter 2, this process improvements shall have as few implications as possible to ensure a successful and fast implementation. Besides this initial effort of narrowing down the demanding signals, the following question must be answered in detail to justify the chosen use case and ensure a successful implementation of the innovation.

Specific: What is the conceptual framework of the solution, improving the identified problem in a simple way? (leading to **RQ1+2**)

4.1.3 Implement (Phase 3)

Implementing the innovation is the key step in the process model and needs to answer the question, how to bring the theory to practice and transform data into knowledge and finally to innovation. Thus, figuring out a practical solution to apply the selected idea is the crucial task of this phase. Moreover, the *Implement* phase consists of three parts from gathering knowledge to launching and sustaining the innovation. Hereby, gathering knowledge requires both existing as well as new knowledge, received from different sources.

Generic: How are we going to make it happen?

The application of this phase follows up on the findings of the previous phase, specifically the finding that TCI data need to be generated first in order to consider TCIs in the planning of construction. Continuing the process, this phase now aims at finding the best way to generate TCI data and integrate it into the existing project information. Here, existing project information refers to the building model with its building elements and the schedule with the construction activities. As part of this phase, a functioning system architecture of the derived process improvement shall be identified. Moreover, a prototype can help to verify the feasibility of the process improvement. This prototype shall be developed and proposed, based on different knowledge from literature and experts. However, by only integrating the new data to the existing process, further development remains static. Therefore, it is crucial to sustaining the knowledge by identifying the applicability of the developed solution and how it can be further improved. To wrap it up, the scope of this phase is translated into the following specific question. It covers the generation, integration, and sustaining of new knowledge in the existing process and thus, containing all requirements of the third process phase of *Managing Innovation*.

Specific: How to integrate the proposed solution within the existing process?
(leading to **RQ3**)

4.1.4 Capture (Phase 4)

The last phase happens after the successful implementation of the innovation and concentrates on the question of how to generate benefits from its implementation. Capturing the value also implies the response of the users. This means that the added value needs to be recognized by the users and facilitate their work.

Generic: How are we going to get the benefits from it?

Added value in this specific use case is mainly determined as improvements in productivity and safety performance in a construction site, but can also refer to other benefits, the innovative solution may provide. In this stage of the innovation development, the focus of the innovation lies on how the relevant stakeholders, who need the innovation, are actually benefitting from it. This phase requires a thorough consideration of the user needs and shall result in a tailor-made process for all different stakeholders.

It further calls for a system that enables an automated assessment of the added value and distribution of the gained information to all relevant stakeholders. By automatically gathering, analysing, and distributing the process data, value can be created and verified to ensure the success of the developed innovation. As this phase *Capture* is regarded as a complementary step in the actual development of the innovation, the generic aspect of this phase will be added to the previous specific question to holistically consider the final steps of *Managing Innovation*. Together, both generic process phases are forming one research question that covers the whole process of developing the innovation in accordance with the main methodology. The following specific question is thus incorporating both the phases *Implement* and *Capture*.

Specific: How to integrate the proposed solution within the existing process and create value for the relevant stakeholders? (leading to **RQ3**)

4.2 Research Questions

RQ0: *How can productivity and safety issues at construction sites be resolved by improving the site and logistics management of temporary construction items?*

In the introduction to the chosen methodology *Managing Innovation*, specific questions were derived from the generic description of the methodology and applied to the research topic. Based on these questions and the identified main research question **RQ0**, sub-questions are formulated guiding the research through the chosen methodology as well as creating an interconnected and understandable research design. Sub-questions must be both, related to the main research question above and linked to the given structure of managing innovation. Furthermore, each sub-question is based on an assumption that is deduced from earlier findings. E.g. **RQ1** is based on the findings of the state of art review and **RQ2** is based on the answer of **RQ1**. This logic helps the reader to follow the red thread of this research (see research structure in chapter 1).
In the following section, each sub-research question (**RQ1-4**) is introduced by its origin, the reason for existence as well as the proposed methods and tools to answer the question. Hereby, the same schema of introducing a subject based on literature and then verifying its relevance with expert interviews is followed as already applied in the state of art review.

A literature review is used for all research questions as it is a powerful data collection method for the initial description. Knowledge production in research has picked up speed tremendously and consequently, reviewing the existing knowledge base is essential to keep up with state-of-art research. (Snyder 2019)

Additionally, expert interviews are supplementing the literature review in order to also acquire current knowledge and experienced opinions from practice. Qualitative research interviews (Kvale 1996) with a semi-structured interview guide are used as they allow to collect important data from chosen individuals, who possess exclusive knowledge about a subject, aiming to understand the context from the individual's point of view and to uncover the meaning of their experience (Brinkmann and Kvale 2015). Moreover, it leverages the development of new ideas during the interview as an interview guide is only semi-structuring the interview leaving the rest to the respective interview flow. For planning, conducting, and analysing the semi-structured interviews, a specific guideline from Kvale (1996) was followed, which is presented in figure 13.

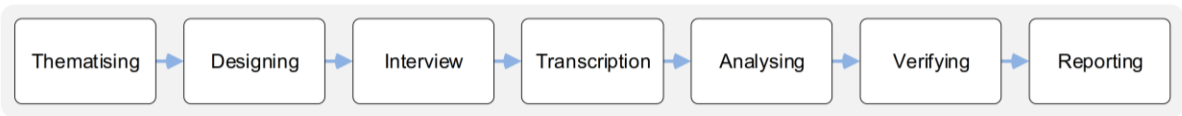


Figure 13: The seven stages of an interview investigation (own visualization)

The interviews were all conducted individually with chosen experts who are introduced in detail in **Appendix 5.4**. The interviewees were selected based on their individual expertise and responsibility within the construction process, while it was intended to get a diverse group of experts within the industry which are all able to add value to the given research questions. As in the state of art review already shown, the interview partners are first shortly introduced and classified in a table format and secondly, the findings of the interviews are presented in the subsequent chapters, exploring and answering the respective research questions. Based on the findings of the utilized methods to explore each step of *Managing Innovation*, the research questions are answered directly at the end of the chapter, where the input for the answer is generated. Firstly, this helps the reader to directly recognize the value, each chapter contributes to answer the respective question and to derive the next chapter. Secondly, answering the sub-questions in consecutive order is following the main methodology of this paper while gradually leading the reader towards the final innovation development and eventually answering **RQ0**.

Concerning the first phase of managing innovation, *Search*, no research question was created as it was already covered by the state of art review in chapter 2, which accomplished the task of identifying signals in the construction industry that call for innovation. As it includes technological opportunities as well as challenges, highlighted from both current literature and construction experts, the *Search* phase is sufficiently considered, forming the baseline for the development of the following research questions.

4.2.1 Research Sub-Question 1 & 2

In other industries, it is documented that efforts in developing a well-functioning information system and information management result in productivity and performance improvements (Banker et al. 2006; Mithas et al. 2011). This evidence should also be transferred to the construction industry, where poor productivity is identified as one of the main challenges. Thus, in reference to the selection task of the innovation process model, the selection for developing an innovation must focus on handling information within the chosen environment.

Framing the research topic in chapter 3 can be seen as the first part of the selection process, contributing to answering **RQ1** and **RQ2**. Yet, what is still missing, is a detailed review of each aspect of the chosen frame. This means, explaining how TCIs are handled traditionally in construction projects and identifying the main problems as well as the most promising solutions for the specific use case. Furthermore, the narrowed-down solution space should be analysed for the specific application in the regarded process. In other words, identifying what is needed to enable the management of temporary construction resources at construction sites. As identified in the practical part of the state of art review, this should not require major changes in the way a construction project is planned. Thus, a simple consideration of TCIs in construction planning is preferred. Based on these requirements, the first two research questions are derived within this phase and will be discussed in detail in chapter 5.1.

RQ1: *How are temporary construction items planned and managed in projects?*

RQ2: *How can this process be improved in a simple way?*

As a result of these research questions, a system shall be proposed, that provides a conceptual solution for an improved planning and management process of temporary construction items.

In order to answer the research questions, an initial literature review (Snyder 2019) brings the required quantity and quality of information for defining the solution. This is then validated by qualitative and semi-structured interviews in which the research selection can be verified by experts in the regarded field of construction management. In this case, Consultant 1 and 2 have already participated in the interview for the state of art report. Hereby, the fact that these interviewees were already involved in the iterative process of defining the solution scope, positively affects the quality of their responses regarding **RQ1+2**. Further experts in the field of providing TCI services and managing construction sites are selected additionally to support the exploration of **RQ1+2**. The interview guide of the interviewee group B is provided in **Appendix 5.2**. The following table introduces each interviewee who participated in the interviews to answer **RQ1+2** and classifies their expert category.

B	Introduction to Interviewees (Group B) – Answering RQ1+2		Experience
1	Consultant 1	Client Advisor at Exigo A/S	+ 5 years
2	Consultant 2	Head of Digitalization at Consultancy A	+ 15 years
3	TCI Provider 1	Head of Department at TCI Provider A	+ 25 years
4	TCI Provider 2	BIM Specialist at TCI Provider B	+ 2 years
5	Client 1	Construction Management/ Supervision for case study project	+ 40 years

Table 3: Introduction to Interviewee Group B

Furthermore, the process of answering both questions will be supported by reviewing a real construction site, using a participant observation role to observe current practice regarding TCIs (Saunders et al. 2016). Moreover, this method allows to include both own experience and the experience of the project participants regarding the research selection for verification purposes.

4.2.2 Research Sub-Question 3

How to bring theory into practice - this is the goal of the third process step of managing innovation (Tidd and Bessant 2012). Hence, this phase serves as the main part of the thesis because it generates real value. Therefore, the research question must address the practical implementation of the proposed solution to capture its value.

RQ3: *How to integrate TCI data to the existing BIM process and with that, create value for the project?*

For the sake of answering this question, an interconnected process of managing TCIs will be established, combining TCI information with the existing data that is commonly created in BIM-planning. This link between the datasets shall enable the integration of TCIs into the planning and monitoring of a construction site by creating a TCI utilization plan for the project. As a result of this, TCIs can be considered in construction management and the created knowledge and transparency about these items shall enable performance improvements in construction. Besides elaborating the process integration from theory into practice, the research question also asks for the creation of value. Adding value in this research means improving productivity and safety at construction sites. Moreover, as identified in chapter 3, the intention is to achieve this by creating an integrated information flow between the planning and execution of construction to improve the overall management of TCIs.

As the research question requires a practical implementation of the previous conceptual assumptions, the answer comprises the development of a functioning tool that can create the needed value. While a literature review would not satisfy this task, a design method shall be used, supporting the development process of an innovation. In this case, first prototyping (Martin and Hanington 2012) is used to create a functioning solution, that is able to integrate data containing information about TCIs, the building model, and the project schedule. The method of prototyping is supported by the auxiliary application of the constant comparative method (Denscombe 2014) in which multiple workshops with experts were used to support the development of the prototype solution in an iterative approach. These workshops support the task of answering **RQ3** by collecting information from experts and use it to proceed with the prototype development. Workshops are mainly held with employees from the company Exigo A/S who have expert knowledge in information technology and construction as well as an external expert who supports the integration of an open data system in the solution. After successfully developing the prototype, the concept solution from **RQ2** is put into practice.

The process of prototyping is conducted with a demo project which was developed for the purpose of concept proofing. Building upon the previously explored theory, the demo project shall represent a simple construction project and provides the required BIM data to develop a prototype solution. The demo project consists of four sequential steps, covering the entire process of a data value chain from data generation to data visualization.

Deriving these steps from a big data value chain and integrating them in the prototyping process offers a structured approach for data management, ensuring a holistic perspective on the complex process and generally generating higher benefits (Faroukhi et al. 2020). In this paper, the big data value chain comprises four steps that are based on Faroukhi et al. (2020) and named as follows:

1. **Data Sources & Extraction**
2. **Data Management**
3. **Data Processing & Querying**
4. **Data Visualization & Distribution**

Combining both the steps of *Implement* and *Capture* in the process of managing innovation, this research question covers the whole process of developing a solution according to the requirements of the main research question. *Implement* is concerning steps number one to three of the data value chain, while *Capture* clearly focuses on the visualization of the raw data and the distribution of the information in order to generate value for all relevant stakeholders.

Developing a solution that enables the integration of new data into the existing BIM process also requires an open and linked data environment. Recently, several research projects have tried to exploit BIM with its full potential by focusing on the information aspect of BIM using Linked Data technologies (Rasmussen et al. 2017). Linking data within the BIM environment is identified as the main challenge for answering this research question, and therefore, this method provides a suitable toolbox to put theory into practice. What Linked Data is all about and how the research benefits from it will be explained in detail in chapter 5.2.2.

As the third process step of *Managing Innovation* furthermore calls for sustaining the developed innovation, the applicability of the prototype solution in the industry must be proven. Thus, the methodology requires the use of an additional method to answer **RQ3**. This method must try to generate the expected value by applying the developed prototype to a real case. In other words, a case study of a real construction project is required to apply the new technology into practice (Moum et al. 2009). Here, the methodology of Yin (2014) is guiding the development of the case study in a linear but iterative approach. Applying the developed solution to a case project allows to validate the developed prototype on a large and more realistic scale than the demo project, further proof the concept of the prototype, and finally answer this research question **RQ3**.

According to Flyvbjerg (2004), case studies possess the power of example which allows the researcher to learn from a specific case in all its complexity and consequently derive a general conclusion. Furthermore, by utilizing a case study, this thesis project follows the recommendation of Harty (2008) calling for more studies that implement innovations in construction projects. The results of prototyping with the demo project as well as with the case study are included in chapter 6 - Solution Development.

Finally, as a result of this process phase, a fully functional and tested prototype solution for an automatic planning and management of TCIs is developed, linking the three datasets TCIs, Building Model and Project Schedule into one solution. By that, the guidance of *Managing Innovation* terminates and although the last two process steps from Tidd and Bessant (2012) address the need for continuous improvement, one relevant aspect has not received sufficient importance in the main methodology of this paper. This aspect is the evaluation of the proposed innovation which leads to one additional research question to holistically develop an innovation.

4.2.3 Research Sub-Question 4

Although **RQ4** is not directly derived from *Managing Innovation*, it follows up on the process steps *Implement* and *Capture* which aim to generate a sustainable innovation that adds value to the construction industry. **RQ4** further addresses the need for verifying the added value.

RQ4: *Can the added value of the proposed solution be verified to ensure its success?*

The research question asks for an evaluation of the proposed solution and thus, a method is needed in this phase to verify its benefit for the targeted stakeholders. That evaluating innovations during the development is especially important in the construction industry was already identified by ASCE (1996). This guide for implementing building innovation provides an enhanced process of evaluating innovations in construction and suggests to integrate "*technical community expertise*" (ASCE 1996, p. 17) in order to evaluate a technical innovation. Further, it determines the importance to technically evaluate and approve an innovation with the expertise from industry experts in the respective technology field. Hence, the highly valuable knowledge of the expert community in the construction industry has to be accessed and utilized to evaluate the status quo of the developed prototype and determine its potential in the industry.

In this specific innovation process, qualitative interviews are chosen to cover the evaluation aspect as they provide a powerful tool to gain detailed insights into people's expertise and opinion. In a statement of Kvale (1996) qualitative research interviews are described as "*attempts to understand the world from the subjects' point of view, to unfold the meaning of peoples' experiences […]*" (Kvale 1996, p. 8). Thus, this method meets all requirements to unlock the knowledge of the technical community expertise and evaluate the potential for the construction industry. Increasing the added value of the interviews, the interview partners are selected from various stakeholders in the construction industry. Furthermore, all interview partners share an affinity and expertise for digitalization in the construction industry. The different stakeholder groups are divided into client organization, consultancy, contractor, and TCI provider. Hereby, the selected experts add value by either being involved in the regarded case study project or by providing their general knowledge and expertise in the construction industry. The following table introduces the interviewees of interviewee group C.

C	Introduction to Interviewees (Group C) – Answering RQ4		Experience
1	TCI Provider 2	Technical Manager, BIM Responsible & Design Engineer at TCI Provider B	+ 20 years
2	Contractor 1	Head of VDC at Contractor A	+ 15 years
3	Contractor 2	Head of VDC & VDC Manager at Contractor B	+ 25 years
4	Contractor 3	Lead VDC Manager at Contractor C	+ 10 years
5	Contractor 4	Head of Production at Contractor D	+ 15 years
6	Client 1	Construction Management/ Supervision for case study project	+ 40 years
7	Consultant 2	Head of Digitalization at Consultancy A	+ 15 years
8	Consultant 3	CEO/ Digital Construction Expert at Exigo A/S	+ 15 years
9	Consultant 4	Digital Development Director at Consultancy B	+ 10 years
10	Consultant 5	Expertise Director ICT, Head of BIM & Linked Building Data expert at Consultancy C	+ 30 years
11	Consultant 6	Head of BIM at Consultancy D	+ 15 years
12	Consultant 7	Senior Consultant at Consultancy E	+ 15 years

Table 4: Introduction to Interviewee Group C

The evaluation process will first highlight the benefits of the proposed solution, respectively for each stakeholder group and subsequentially explore the need for further improvements.

Lastly, a potential business model is investigated with the input of the interviewees. The analysis of the interviews as one process step of conducting qualitative interviews (cf. Figure 13) is applied here more in detail as the evaluation of the proposed solution is regarded as a major contribution of this paper to the construction industry.

The analysis of the interviews is carried out after the qualitative content analysis (Mayring 2014). The categories, which classify the collected data according to their content, were mainly derived from literature and prior findings in the thesis development. Some categories also emerged after conducting the semi-structured interviews directly from the interview data and complement the previously developed categories. Therefore, the approach for analysing the conducted interviews can be described as a combination of deductive (category forming based on theory) and inductive (category forming based on interview findings) research. According to Mayring (2014), both the deductive and inductive approach are central parts of the qualitative content analysis and therefore, add value to answer the last sub-question **RQ4**. The following figure shows the deductive categories, used to systematically analyse the interview output and categorize the main findings. The categories are divided into the four groups Current Practice, Benefits, Evaluation, and Business Model. During the analysis of the interview data, the categories are inductively checked for validity and supplemented if necessary, according to the interview findings.

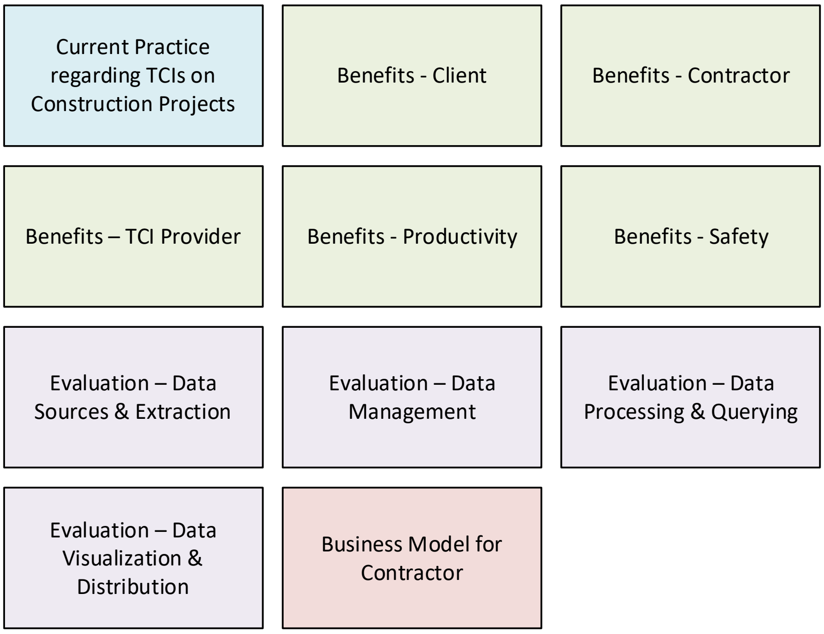


Figure 14: Deductively developed categories for content analysis (own visualization)

Based on the developed categories, an interview guide was developed that allows to structure the semi-structured interviews in a solution-specific way. The interview guide contains open questions in order to unlock the knowledge of the interviewee regarding each of the developed categories. The entire interview guide can be found in **Appendix 5.3**. During the interview, the interview guide requires to first introduce the interviewee to the developed solution with a detailed presentation (**Appendix 5.5**) in order to increase understanding and familiarize the interviewee with the scope and status quo of the solution. Consequently, the interview guide then intends to go through the interview questions that are based on the deductively developed categories. By concluding the last step, the evaluation, a functional solution is developed and evaluated by a valid representation of 12 experts in the Danish construction industry.

4.3 Summary of Research Design

By answering **RQ4**, the last step of the innovation process will be completed. It is assumed that the combination of all answered research questions will fulfill the **research objective** by providing an innovative and validated solution for improving productivity and safety at construction sites by applying information technology in the planning and management process of TCIs.

To facilitate the understanding of the derived research questions and giving a short summary, figure 15 recaptures all research questions with their respective methods in relation to the methodology *Managing Innovation* (Tidd and Bessant 2012).

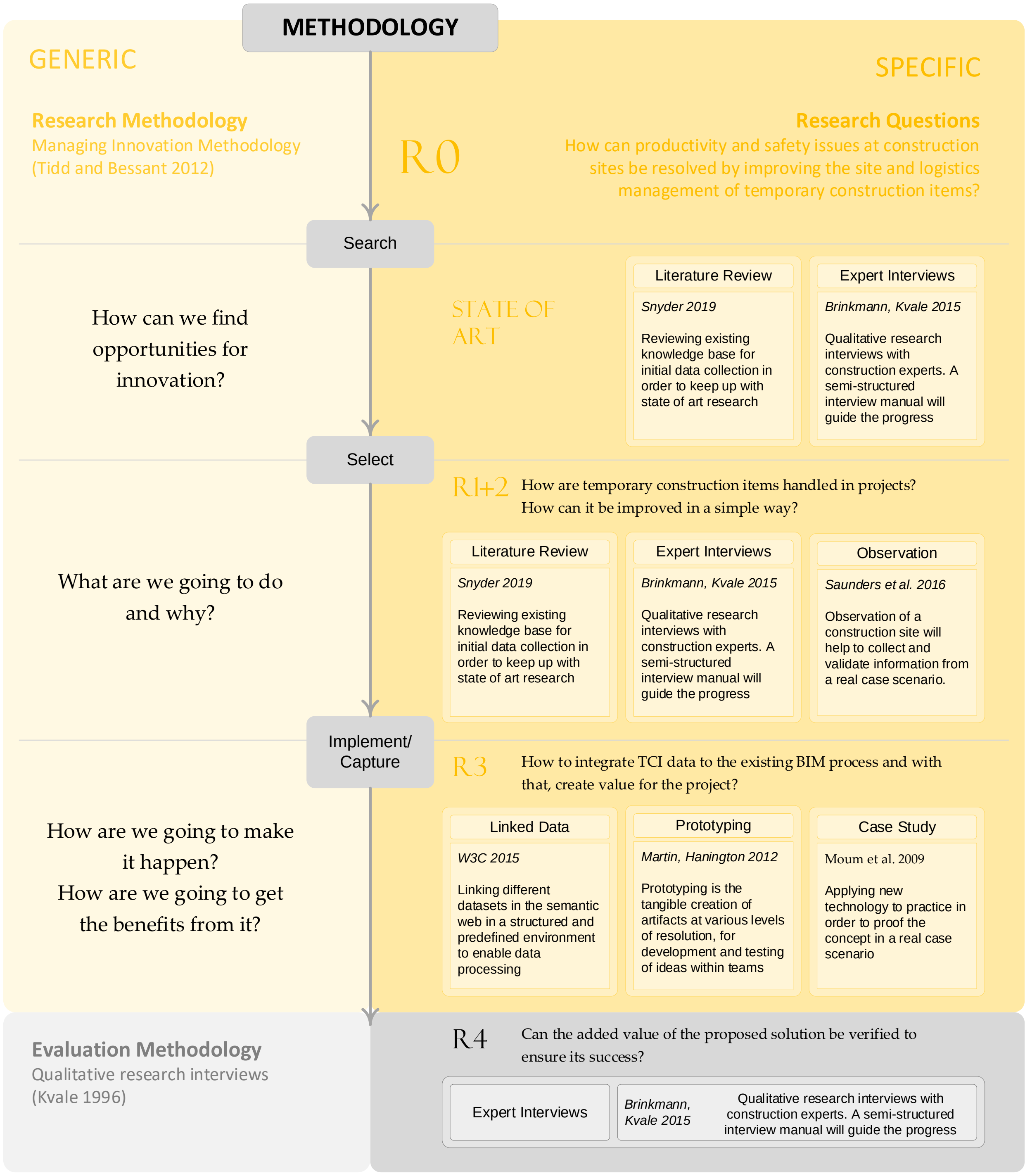


Figure 15: Research methodology and derived methods (own visualization)

Based on the just developed methodology chapter, the next chapter will document the innovation development process of the proposed solution, going from the idea definition over prototyping towards the establishment of a validated concept solution that answers the main research question **RQ0** and tries to solve the identified problems from chapter 2.

Chapter 5: Concept Development

Having determined the research methodology with one main and four sub-research questions, forming the scope of the research, the purpose of the next two chapters are generating the input to answer the determined research questions. As the research design already revealed, the answer to each question is used to subsequentially answer the next questions. Thus, the sub-research questions are answered in the following two chapters and the findings contribute as justification to progress with the next research question. The findings and answers to the sub-questions will further serve as the basis to answer the main research question in chapter 7 - Discussion.

This chapter is exploring the concept development of a solution that addresses the identified problem and solution space and is providing information to answer the first two research questions. Both **RQ1** and **RQ2** are part of the selection phase of the main methodology and are analysed in chapter 5.1 and 5.2 by introducing first the findings from a literature review and further examining the topic with input from expert interviews. In this case, chapter 5.1 is dedicated to giving a detailed overview of how TCIs are currently handled on construction sites and how this can be improved within the given **research objective** to answer **RQ1**. Furthermore, a suitable type of TCIs will be chosen as a sample representation of TCIs for the further solution development. The second part of chapter 5 is exploring the conceptual solution framework, how the selected TCI type can be integrated into the existing BIM-based project delivery. Here, chapter 5.2.1 focuses on the planning of TCIs and draws a conceptual framework of the proposed solution, whereas chapter 5.2.2 explores the information management system of the proposed solution. Together, both chapters provide sufficient information to answer **RQ2**. The resulting concept solution is then subject to be further explored through a practical development in chapter 6 - Solution Development, where two separate subchapters are created for presenting the findings of the initial prototype development as well as the case study application.

5.1 Temporary Construction Items (Answering RQ1)

Temporary construction items are identified as a risk factor on a construction site, accounting for productivity and safety issues due to a lack of attention in planning and construction management. As TCIs are the principal focus area for this research, this chapter provides a thorough introduction to the topic and verifies the assumptions from literature with findings from interviews as well as a construction site observation.

Literature Findings

"*Temporary structures in construction are those structures that are erected and used to aid in the construction of permanent projects*" (Ratay 2004, p. 292). Mostly, these items are erected to facilitate a specific construction activity on site and get removed after the permanent work is self-sustaining or complete. Facilitating the construction process is the main purpose of TCIs while they receive secondary attention in planning and management but have a primary impact on the outcome of construction projects. Traditionally, these items highly impact construction in terms of time, cost, quality, safety, and efficiency (Beale and André 2017) due to their quantity as well as their labour and time intense installation processes (Wu et al. 2018). Moreover, TCIs are "*reused many times*" (Beale and André 2017, p. 447) during the construction project and therefore, the positive impact of planning TCIs is increasing with the size and time of the construction project. In practice, the consideration of TCIs is realized late in the project, just before construction starts on site. Designing architects and engineers usually do not include specifications or design requirements of TCIs in the building design (Beale and André 2017). The entire responsibility of selecting and procuring TCIs holds the construction manager. He plans the amount and types and often orders the equipment from an external supplier without collaborating with the design team and their already made efforts and knowledge regarding the project (Ratay 2012).
Thus, the work of the TCI-responsible is often reactive and based on a manual assessment on a daily basis, which is leading to several problems on site. To name a few, inefficient construction workflow, wasteful procuring as well as site & logistics management of TCIs (Kim et al. 2016a). However, Teizer (2015) notes that successful and modern construction projects must adequately plan and manage all resources on the construction site, also including TCIs.

Furthermore, this paper mentions that most issues are related to tasks for maintaining the schedule and therefore, there is a need to first plan all resources and then execute the project according to the plan as well as monitor progress with updates regarding task completion. This allows to properly allocate TCIs early, before they are needed in the schedule, facilitating the coordinate and execution of next construction activities. The following table shows an example from current practice, what types of and how TCI planning & budgeting is carried out.

Construction site employment	
Construction site layout	hours
Assembly office modules	stk
Assembly toilet box	stk
Establishment of electrical installations shed	sum
Establishment of electrical installations	sum
Establishment of lighting in public areas	sum
Establishment of IT/phone installations	stk
Etablering af vandinstallationer	sum
Crane (semi-mobile crane) 35 m / 1,300 kg	stk
Crane (tower crane) 50 m / 2,700 kg	stk
Crane foundations 7 x 7 m	stk
Material lift	stk
Person - and material lift	stk
Construction site fences	m
Fence gates	stk
TCI materials (formwork, supporting structures)	stk
Construction site roads	m2
Construction site storage	m2
Construction site paving shed	m2
Laying of walking plates	m2
Transporter small	stk
Transporter big	stk

Construction site operation	
Scaffold	m2*mon
Formwork	m2*mon
Supporting beams	stk*mon
Material container	Mon
Smaller machines and hand tools	man hours
Crew modules 10 men	Months
Office modules 2 rooms	Months
Toilet box	Months
Office set furniture	Months
Cleaning sheds	stk*mon
Electrical installations rental	Months
Crane (semi-mobile crane) 35 m / 1,300 kg	months
Crane (tower crane) 50 m / 2,700 kg	months
Material lift rental	months
Person - and material lift rental	months
Fence construction site rental	m
Building lift rental	months
Safety protection	m
Waste management	sum
Laying of walking plates rental	sum
Transporter small rental	stk
Transporter big rental	stk

Construction site dismantling	
Disassembly of office & modules	stk
Disassembly of toilet boxes	stk
Disassembly of scaffolding untis	m^2
Disassembly of formwork	m^2
Disassembly of supports	stk
Crane semi-mobile down	stk
Crane tower down	stk
Material lift down	stk
Person - and material lift down	stk
Construction site fence down	m
Transporter small	stk
Transporter big	stk

Table 5: Site budgeting example from Exigo A/S for site layout planning

Table 5 shows an exemplary budgeting example for the site layout planning with respective TCIs and their specific measurement units. The table covers the three phases of construction, site employment, operation, and dismantling and gives the construction manager an overview of the items to consider in the site layout budget. In current practice, such a table allows the construction manager to roughly estimate and plan all resources that are needed on site and derive their respective budget. However, as there is no link between the model properties of the permanent building and the TCIs, the issue with such a solution is that this task is very labour-intensive and manual and can only provide a rough estimate based on what has yet been planned (Kim et al. 2016a). Thus, a data-driven and integrated tool to estimate TCIs is required (Kim and Teizer 2014).

Interview Findings

During the expert interviews for this chapter, the resource table (Table 5) was presented to the interviewees as a reference, introducing the discussion about the necessity to include TCIs in planning and management of a construction project and which TCI-consideration would have the most potential.

Based on the conducted interviews, general accordance regarding the fact that TCI planning and management are neglected in construction projects was identified. All interviewees stated that an (early) consideration of TCIs for construction planning and management would add value to the construction process on site due to the enhanced transparency and knowledge of these items. With the information about TCIs, one can then simulate the construction site and logistics via BIM, both considering the permanent construction and its supporting temporary items. In this regard, Client 1 as a BIM Manager from a TCI supplier claimed that decisions about TCIs already have an impact in the design phase, but the effort of considering TCIs still mainly takes place late during construction. He also revealed that from the supplier side, it is intended to get actively involved at the beginning of a construction project to already place the expertise and include TCIs in the BIM planning process. Similar services are also offered by the company of TCI Provider 1. However, this active role is often not part of their contract. In most cases, as confirmed by Consultant 1 and TCI Provider 2, the supplier is not integrated into the site planning & logistics. Therefore, a more common practice, according to Consultant 2, is to just estimate the cost impact of TCIs as a percentage of the total costs and shift the responsibility of detailed planning towards the subcontractors.

As current best practice suggests, TCI planning can be written in the job description for the site facility supplier on any project, as mentioned by TCI Provider 1, and by that assigning the responsibility to an appropriate party. According to Consultants 1 and 2 however, in practice, this is not often realized due to the little attention, TCIs experience in general. Hence, the project is lacking a simple consideration of TCIs that can be applied in practice without major implementation effort. The neglection in planning furthermore leads to difficulties in invoicing, as described by TCI Provider 2. On their construction site, TCIs were estimated in the contractor's contract and invoiced based on this estimate. However, the real quantities and usage might differ from this rough estimation, leading to wrong payments and inefficient TCI allocation on site.

Due to this little transparency in the process of budgeting and invoicing of TCIs, the client-side has to conduct labour-intensive inspections on site in order to validate the quantities of TCIs that the contractor is charging, as revealed by Client 1. TCI Provider 2 also mentioned an example in which numerous fences for separating roads from walkways were missing on site, but were invoiced nonetheless, due to the untransparent planning process. Having transparent information about TCIs, in contrast, would allow to issue justifiable invoices, based on actual quantities. In reference to the list of TCIs (Table 5), all interviewees stated that this simple budgeting tool would give a great overview of both cost and resource-wise of TCIs on site. In reality, however, such a list is barely utilized by the construction management.

Not planning TCIs in the first hand, also highly impacts the later management on site. Both Consultant 1 and Client 1 added to this point, that there is a general issue with too many items on site which are not used because the order of these items is based on a rough estimation, aiming to always have enough TCIs on site without having detailed insight about their spatiotemporal utilization. This practice leads to inefficient construction processes and avoidable rent. In this aspect, Consultant 2 recalled an exemplary situation on a construction site where the construction manager wanted to find a movable working platform, but they could not find the item for two years and nobody knew where it was located. Eventually, more money was paid in rent, than a new platform would have cost. This example clearly reveals the indifferent attitude of the construction management towards TCIs.

This indifference and lack of attention continue throughout the whole construction phase, creating untransparent material flows as well as impeding lean site management. Consultant 1 described the current practice as an inefficient and iterative process without a look-ahead plan. According to both Consultants 1, 2, and TCI Provider 2, no information regarding TCIs on site means inefficient storage of items and an oversized stock of TCIs to prevent shortcomings, resulting as well in a lot of inefficiently used space on site. Having transparency with updated information about TCIs based on the construction progress would, in contrast, enable just-in-time delivery and lean management of the items for each phase from delivery, storage, and utilization over dismantling and reuse to returning the elements to the supplier. Hence, monitoring TCI utilization would be a logical consequence, adding value as veracity and detail to construction management (Teizer 2015; Turkan et al. 2014).

Neglecting TCIs in the planning and management of a construction project can significantly intensify cost and time overruns (Wu et al. 2018). In some construction projects, as described by Wu et al. (2018), TCIs even constitute the most expensive part of the total costs.

Moreover, errors and uncoordinated management of temporary structures are causing safety hazards (Prof. Kamran M. Nemati 2019). In contrast to the common practice, knowing safety risks of specific items and when as well as where they are used by whom would allow mitigating safety hazards (Kim et al. 2018). As Client 1 already explained, TCI suppliers would have the expertise and tools to integrate a TCI utilization plan into the BIM-based planning and management of a construction project. However, this practice has not yet been considered frequently and early integration of subcontractor with current project delivery methods is difficult to achieve.

Concluding the initial findings from the interviews and literature, the importance of proper planning and management of TCIs for productivity and safety reasons is highlighted and thus, validates the **research objective** of this thesis.

For the development of a prototype, one type of TCIs must be selected as a suitable representative for all TCIs. Therefore, the interviews also serve as a platform to iterate different types of TCIs and evaluate their appropriateness and impact of consideration. To the question, which management process of TCIs has the most potential to be improved, Consultant 1 stated that more detailed information, especially about items that are often used and moved around on site, would have a positive impact on the site & logistics management. Among such items count for example formwork, scaffoldings, or supporting structures. Bigger machinery also highly impacts construction success, but according to Consultants 1 and 2, these items are generally sufficiently integrated into construction planning. This is reasonable as a single machine accounts for a lot of value and thus, has a direct and visible impact. TCI Provider 1 furthermore identified all interim installations on a construction site, including electricity, light, water, machinery, construction site lifts as well as formwork, scaffolding, or fencing to cause difficulties on a construction site. Besides that, he also mentioned that embedding TCIs already in the tendering process will have a positive impact on the spatiotemporal management of TCIs in general as the dimension space and time for these temporary structures are considered early in the project. This statement is highlighted by TCI Provider 2, who stated that obtaining information about TCIs early in a project would allow to include them in a time- and location-based schedule.

In this context, Kim et al. (2018) explain that temporary structures as scaffolding, formwork, and shoring are the types of TCIs that are mainly influenced by their spatiotemporal properties. Thus, combining the two statements from TCI Provider 1 and 2 with the fact of the presented paper leads to the conclusion that TCIs as scaffolding, formwork, and shoring can benefit the most from an (early) consideration in site & logistics management. Wu et al. (2018) support this conclusion by claiming that TCIs, "*such as formwork and scaffolding, play a significant role in the proper planning and smooth progress of construction projects*" (Wu et al. 2018, p. 1). Consultant 1 furthermore explained that there is a need to gather and process information about all resources that are directly affecting or facilitating value-adding construction activities. As a matter of fact, formwork and scaffolding are part of these TCIs that can be directly linked to a construction activity.

As identified by almost all interview partners, the most difficulties regarding site & logistics management are posing items that are frequently moved around a construction site or directly affect the value-adding activities. The most prominent member of this group, according to the interviewees, is formwork, which directly supports the construction of in-situ concrete elements. Supporting concrete walls, columns, and slabs, formwork is usually used in a complex collaboration with supporting beams and scaffolding to facilitate the whole process until the elements achieved sufficient self-supporting strength (Turkan et al. 2014). In a single project, formwork is used hundreds of times, being erected, loaded during the concrete pour, and dismantled for future reuse (Ratay 2012). Referring to construction projects with mainly in-situ concrete elements, formwork is identified as the largest cost component of the structural frame (CRSI 2000; Peurifoy and Oberlender 2011; Hurst 1983). This fact is further underlined by the following figure .

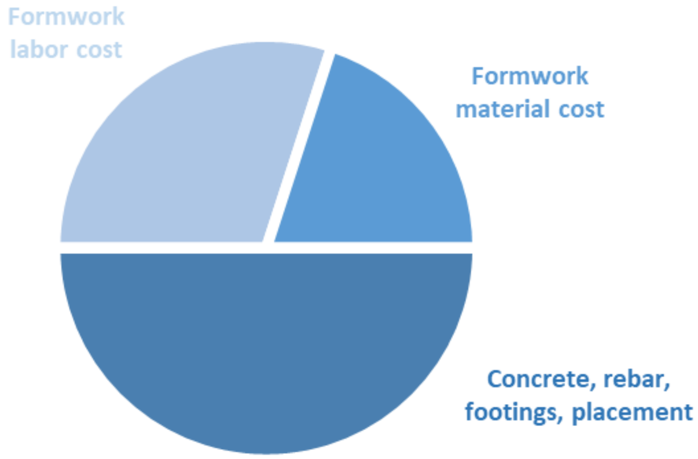


Figure 16: Costs of erecting a concrete building part (own visualization)

Figure 16 illustrates that formwork costs are the biggest portion of the concrete costs that are controllable by the contractor (Ratay 2012). Prof. Kamran M. Nemati (2019) even states that formwork costs account for up to 60% of the total concrete cost in a project. A similar number was published by Sattigari et al. (2007), stating that formwork makes up approximately 40% of the cost and 60% of the time for any in-situ construction activity. Other sources mention that formwork comprises 15% of the total construction costs (Wu et al. 2018). In the case of formwork, the costs are typically split up into formwork related labour cost and material cost, as shown in figure 16. Furthermore, formwork utilization constitutes to the accident types *striking against or struck by moving object* and *trapped in between objects*, identified by Shafique and Rafiq (2019) to be among the most frequent fatal cases (cf. chapter 2.1.1). Thus, a focus on formwork for representing TCIs in the process of prototyping is considered a valid and justifiable limitation for the development of this thesis project.

Integrating TCIs in the project schedule, offers the construction manager transparency and a clear picture of when, how much, and what type of TCI is needed on site and with this, a lean management of these items is possible. Lean in this matter means keeping the on-site-stock of TCIs to a minimum, enabling just-in-time deliveries, establishing specific and dynamic laydown areas for TCIs on site, and creating an on-site logistics plan which supports a continuous and efficient flow of all construction activities. In consequence, a lean management process of TCIs will reduce waste in all construction processes as well as the cost of renting TCIs. Labour related cost is also reduced as all required elements, facilitating an activity, can be prepared and moved to the accurate location before a task is supposed to be carried out according to the schedule.

In fact, 60% of time regarding the task sequence in formwork operations can be saved with a better planning, standardization, and monitoring (Ratay 2012). The high impact of standardization is also mentioned by TCI Provider 2, as standard forms make approximately 95% of the used forms on a construction site. The advantage of standard products is clearly the plannability as all variables are already known. Improving the planning of standard formwork also needs to comprise the entire task sequence of a construction activity, including specific information about the involved items. The standard sequence of a formwork operation, for example, consists of 6 phases, which is derived from Ratay (2012) and illustrated below.

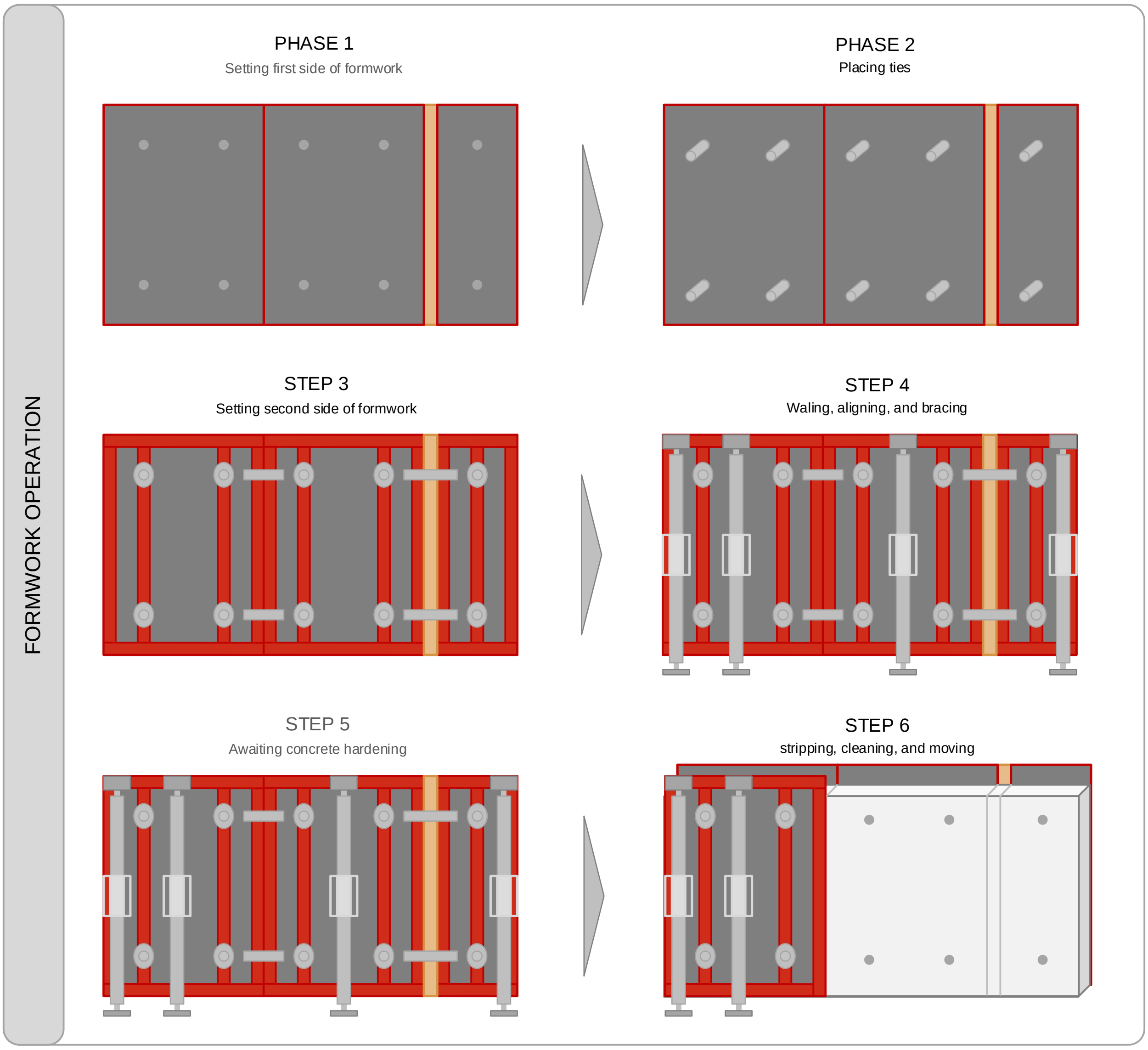


Figure 17: Formwork operation in 6 phases (own visualization)

Involved items in the process of formwork utilization are, for example, panels as the primary formwork elements and supporting items (secondary formwork elements) as coupler, walers, ties, and bracing (mainly push-pull props).

Beneficial information to consider for planning this process, according to Client 1, is the count of each type and properties of primary formwork elements as dimensions, weight, static capabilities, and information about secondary formwork elements that support the use of the primary elements. Additionally, how-to-animations for the installation and dismantling of formwork elements were identified as good practice as they assure proper and risk-free handling of the elements. Further information that should be considered when planning formwork is categorized as status information by Client 1. In this category falls all information about the timely usage of the formwork elements, including information as "ordered", "delivered", "stored", "in use" and "ready for pick up". The status "in use" again can be divided into the status "installation", "ready for concreting", "concrete pouring", "concrete hardening" and "dismantling". Required data to include this status information in the formwork planning is obtained by progress monitoring of the construction processes, on the one hand, and by time requirements for specific tasks in the sequence (Turkan et al. 2014; Ratay 2012), on the other hand. The main requirement, on which formwork operation depends, is the form stripping time, meaning the time the formwork and supports have to remain in place before dismantling. This time can be derived from standard codes as the ACI 347-04. This information regarding the use of formwork is summarized and publicized by Ratay (2012). A few examples are listed as follows:

- Form-stripping time for vertical formwork, covering a wall: 12 hours
- Form-stripping time for vertical formwork, covering a slab:
    - Clear span between structural supports < 3 m: 4 days
    - Clear span between structural supports 3 - 6 m: 7 days
    - Clear span between structural supports > 6 m: 10 days

With the above-mentioned information, a standard formwork sequence can be developed, describing the process of formwork utilization and considering both what can be defined beforehand by standardization and experience, and necessary variables, yet to be defined.

Additionally, it deduces the time dimension by integrating standard form-stripping times and productivity rates based on guidelines and studies.

An additional parameter, that is of value when planning the formwork utilization is a safety-risk factor for formwork operation. Following the safety guidelines for formwork operations from the Scaffolding, Shoring and Forming Institute (SSFI), and from other national institutes as the Occupational Safety and Health Administration (Osha) in the United States and the Infrastructure Health & Safety Association (IHSA) in Canada, safety risks within the operation of formwork can be determined for the applicable formwork types during construction planning (SSFI; OSHA 2018; IHSA 2019). With that, safety hazards can be addressed specifically for each formwork operation task, improving the safety awareness of the construction workers (Ratay 2012). Based on these guidelines about safety, a Safety-Risk-Factor (SRF) can be derived for specific formwork types and operation tasks. An SRF is regarded as a valuable parameter to be included in planning and managing formwork and will be explored more in detail in chapter 6.1.1.

Site Observation Findings

As identified above, proper planning and management of TCIs and especially formwork on site can have a significant positive impact on productivity and safety. In order to validate that a process improvement in this field of interest has potential, an actual construction site is observed to identify challenges and waste in current practice. Reviewing a real construction site, using a participant observation role (Saunders et al. 2016), allows to obtain unaffected information from a real-life situation, verifying the assumption that there is a need for a better planning and management of TCIs. Linking the academic research with a case study further facilitates the verification of the proposed solutions regarding the expected benefits. After developing the solution, it can be applied and tested on the already observed project, which allows identifying the added value. An informative introduction to the project is also subject to the case study in chapter 6.2. Findings of the site visit where the observation was conducted, are documented in a photo documentation and can be found in **Appendix 2**. As follows, the most relevant results of the observation are summarized, and a general conclusion is given, verifying the research scope.

Figure 18: Photos of the site observation (04.06.2020)

Generally, the construction site was well planned and functioning, although a few issues regarding TCIs have been identified during the observation and participant interviewing. Construction workers, for example, claimed that detailed information about the usage of TCIs is lacking and only based on ongoing estimations. Figure 18 also exemplary shows several items that are just laying around the construction site, blocking access paths, or causing safety hazards for the construction workers. This was a common issue on site but considered a minor problem by the construction workers as this situation is what a construction site normally looks like. Most of the identified issues were also related to the application of formwork, highlighting again the relevance of formwork, representing TCIs in this paper. Justifying the research scope, these identified issues are assumed to be common practice on most construction sites.

Summarizing the findings of this chapter, figure 19 shows a flow chart of current practice on how formwork utilization is estimated, controlled, and managed on site. The chart is based on Kim and Teizer (2014), where a similar approach is explored for automating the process of scaffolding planning. In this application, the chart shall first present the current practice of formwork utilization. The same chart is then recaptured in chapter 6.1.4 to compare it with a revised version, that is based on the proposed solution and incorporates an automatic planning tool for the formwork utilization. Having a modified perspective on estimation, controlling and management of formwork from the proposed solution will later help to address the gained benefits of the process improvement.

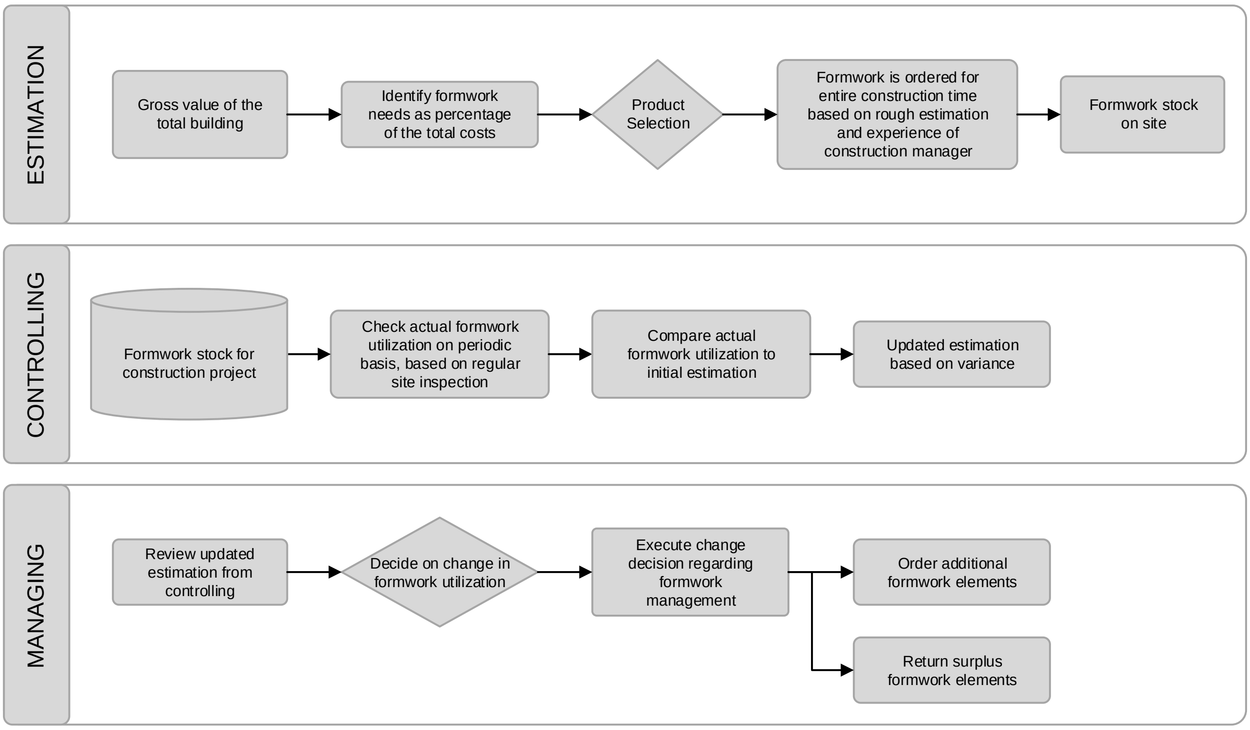


Figure 19: Formwork estimation, controlling and management (own visualization)

Concluding this chapter, formwork constitutes the main portion of the total installed cost of in-situ concrete structures and has a significant impact on the construction time and safety. Hence, improving the efficiency of storage, logistics, and use of these items can speed up the construction schedule, reduce waste, cut costs related to rent and labour as well as positively impact safety on site.

Covering input from literature, interviews as well as a site observation to answer the first research question, regarding the current practice of planning and managing TCIs, exemplified by the use case of formwork, this chapter intensively explored the scope of **RQ1** and provides a well-balanced answer to the first research question. Based on this answer, the following chapters will intensify the process of developing an innovation by first drafting a conceptual framework and then develop a prototype solution that is eventually answering the main research question **RQ0**.

5.2 Framing the Conceptual Solution of TCI Integration (Answering RQ2)

By answering **RQ1**, chapter 5.1 accomplished the first step of the **research objective**. As the second part of the *Select* phase of *Managing Innovation* (Tidd and Bessant 2012), this chapter subsequently further explores the scope of the innovation to be developed. Hereby, a simple way to consider TCIs in construction planning is examined on the basis of a literature review, expert interviews as well as a site observation of a real construction site. After proposing a process of integrating TCIs into construction planning and management, a successive chapter recommends an integrated project environment for managing and sharing data that is applied as a central part of the proposed solution. The findings of both chapters provide the answer to **RQ2**.

5.2.1 Simple Way to Consider TCIs in Construction Planning

The previous chapter revealed a need to first include TCIs in the planning process of construction sites to overcome current challenges in a construction project regarding productivity and safety. Formwork is selected as a potential application area as it has a significant impact on cost, schedule, and safety on site (Prof. Kamran M. Nemati 2019). Furthermore, the interviews of Consultants 1 and 2 also revealed that individually modelling these entities in the BIM-model would allow better planning but requires a huge manual effort. Hence, it will be difficult to successfully implement this approach in the industry. In this regard, Consultant 1 claimed, that a relatively easy consideration of TCIs would be to create a relation to already existing planning and management efforts and by that link TCIs to permanent building elements. Hence, such a simple way to consider TCIs in construction planning is explored in this chapter.

Firstly, literature is reviewed to find innovative and simple solutions on how to consider TCIs in planning. Secondly, expert interviews with professionals in the field of digitalization in construction are conducted to receive further input from a practical perspective. Recapturing the site observation, impressions from the construction site are utilized to derive the potential and possible benefits of the proposed concept solution. Lastly, the focus area of the proposed management process for TCIs, which was conceptualized in chapter 3 will be further explored and explained in detail, providing the main contribution of this chapter to answer **RQ2**.

Literature Findings

Planning of TCIs in a construction project is a huge challenge in current practice and is often neglected (Kim and Teizer 2014). However, it is stated that "*a correct choice, good planning, designing and operation of temporary structures are keys for the success of every construction project*" (Beale and André 2017, p. 439). Planning of TCIs requires spatiotemporal information to be analysed as these items are frequently reused on site and change their location and application over time on a daily basis (Beale and André 2017; Kim and Teizer 2014). In consequence, the required information has to be obtained for a proper decision-making approach.

On the one hand, there is a need for data integration of both the geometry of the construction and location-based schedule information from BIM planning applications with data about TCIs. On the other hand, a logic needs to be developed which automatically analyses the given geometric conditions of permanent works and allows to deduce the respective use of TCIs according to the geometry (Kim et al. 2018). By developing a system that integrates and processes all data, automatic planning of TCIs in relation to geometry and schedule of permanent construction items (PCIs) can be established which provides useful information for all relevant stakeholders to improve construction and logistics management on site.

However, currently available tools do not enable such an approach and there is also little research conducted. Thus, this research aims to develop an integrated tool that links all required data for planning and managing TCIs in a simple and accessible way from which the construction industry can benefit. This tool shall assist construction managers in their decision making by utilizing the existing BIM data and integrating it with TCI planning rules in order to automatically develop a TCI utilization plan for more transparency and a proactive management.

Following the principles of Kim and Cho (2015), the first step of automating the planning process of TCIs is the development of rulesets. Rules define the basic logic of how a specific TCI is planned in relation to the permanent building parts. Here, every TCI-type requires a different ruleset to enable automatic planning as the logic of planning differs. In this case, rules are based on the application of formwork and are derived from the previous chapter. These rules are then translated into an algorithm that helps to provide the logic in a machine-readable format, in order to integrate it with BIM data (Kim and Teizer 2014). According to each defined rule, specific data need to be extracted from the BIM model and the schedule.

When linking all required data into one tool, the algorithm allows to derive information about the TCI demand and hence, enables an automatic planning process of TCIs based on the BIM model and schedule data (Kim and Cho 2015). Kim and Teizer (2014) also explored this research area with the focus on scaffolding systems. The proposed computational algorithm can analyse a building model regarding the geometry, identify locations in the model that need scaffolding and automatically develop the scaffolding system (Kim and Teizer 2014). In accordance with Kim and Teizer (2014), developing an algorithm for this research should comprise the following 4 steps:

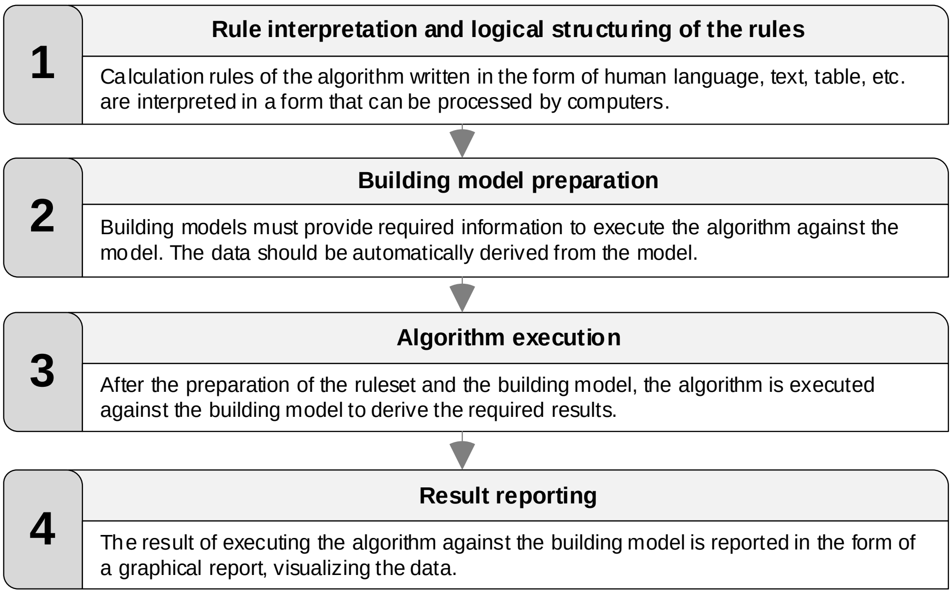


Figure 20: Steps of developing an algorithm for automatic TCI planning (own visualization)

In order to develop an algorithm that fits the scope of this thesis, the ruleset needs to be established to reflect the planning of formwork. Lee et al. (2009) developed a tool that generates the formwork layouts based on design requirements and Sattigari et al. (2007) created an engine that captures spatial data of a building object from a drawing and uses a rule-based algorithm to derive a formwork scheme. Both inputs of these papers and from experts for formwork planning are utilized to create the logic for the automatic planning of formwork in chapter 6.1.3.

Regarding the **research objective**, the rule-based algorithm that can calculate the TCI demand must be integrated into the data environment to automatically analyse the BIM data and derive a TCI-utilization plan according to the building model and schedule.

After developing rich information about TCIs for a specific project, the information must be shared with all relevant stakeholders. As identified by Beale and André; Kim and Teizer (2017; 2014), successful project delivery can be accomplished if "*continuous knowledge exchange and synchronised planning*" (Beale and André 2017, p. 439) of TCIs with all relevant stakeholders are established. How this data integration and information exchange can be done in practice will be elaborated in the next chapter. Before that, findings from expert interviews help to further discuss on the automatic planning approach for TCIs from a practical perspective.

Interview Findings

According to Consultant 1, every specific construction task of the permanent building structure is enabled and facilitated by the use of specific TCIs. Given the fact that building tasks are generally the same in all construction projects, just with another scaling factor, the idea of linking permanent building elements to TCIs was decided to be an efficient solution. For the deduction of realistic TCI-quantities, a logic needs to be created that takes into account data regarding TCIs and establishes a relation to the existing BIM data. Based on this idea, Consultant 2 mentioned that the best way to do that is by using a rule-based algorithm that contains the required relationships. This statement is also approved by TCI Provider 2, who elaborated on the possibility to use an algorithm that takes in information from the building model and the available TCIs and calculates TCI quantities based on their relation to the permanent building elements. Client 1 continued that obtaining information about TCIs as easy and quick as possible must be the primary objective of the solution, hence, deriving the information from what is already existing. De facto, as Consultant 1 strongly highlighted, this logic can be established beforehand and reused with smaller adjustments for several projects.

As a result of this, every building element is regarded as a location-based construction activity and receives information about what type and quantity of TCIs are needed to complete the task. Consultant 1 framed this approach of not actively tracking each TCI, but tracking the task which is related to specific TCIs, with the following principle: "*You have planned it [each element of a building] because you know the size of it. And you can plan that they need this much formwork to do this activity in that location. It is about making a small ecosystem where it is all integrated.*" (Consultant 1, 19.02.2020).

The outcome of this would be a location-based utilization plan of TCIs for the entire construction project and as Consultants 1, 2, and Client 1 iterated during the interview, this information allows one to simply track the temporary items on site through the progress monitoring of the permanent building parts. Based on the real-time information form the progress monitoring, one can then adjust the site management and logistics planning of TCIs as well. Thus, only one input is needed during construction that provides highly valuable information about TCIs as cost, schedule, usage, storage, logistics, and the site operation because all data is available beforehand. Hence, a system must be established where all required data is integrated. The result of this linked data environment enables a passive activity tracking of TCIs through their respective and related building elements.

Client 1 also explained that an automatic planning of TCIs needs to be based on rulesets that are derived from assembly and use manuals of the respective TCI type, but also each specific product. A simple program or software application should then be used to calculate TCI quantities in relation to the building elements and their geometries. Moreover, Client 1 mentioned that some TCI suppliers already developed applications that can calculate TCI quantities based on building model geometries. As these applications are product specific and not publicly available, a consideration of these applications in the proposed open data solution in this thesis is not regarded as valuable.

The benefit of a passive approach of planning TCIs, in contrast to modelling TCIs in a BIM application, is that it provides all needed information with the least effort. Consultant 2 supported this by saying that the geometry of TCIs is not needed in a model and therefore a rule-based interpretation and quantity take-off of these items with location information is sufficient. The data about TCIs can then be visualized on a location level in a schedule viewer to review what type and how many TCIs are needed where and when on site rather than on a detailed model level. From both Consultant 1 and 2, this approach was also regarded as much more efficient and simpler in comparison to the implementation of IoT-sensors for an active tracking of TCIs. As soon as the system is implemented and works, however, it can be further improved by integrating IoT-tracking data as it would allow to obtain real-time location data about TCIs which allows to compare the supposed location from the passive tracking with the real location from the IoT-sensor. This was both confirmed by Consultant 2 and Client 1.

According to Consultant 1 and TCI Provider 2, this system of considering TCIs in construction is able to raise productivity and safety as well as reduce waste on the construction site. For Client 1, this positive impact of the solution is even more obvious. In his opinion, having a plan and real-time information about the utilization of TCIs always improves productivity and safety on site. A further extension of the solution was mentioned as to equip the developed data environment with ISO standards and safety regulations. This information can then be part of the data visualization, increasing the safety awareness and proper handling of TCIs.

Consultant 2 furthermore added that automatic planning of TCIs has some positive impact on costs but most of the benefits will come from time savings as it enables lean site management. TCI Provider 2 continued that the contractor mainly benefits from the solution because one would always know when the TCIs have to be ready for upcoming tasks. This transparency creates knowledge about what types and quantities are right now on site and will be needed later. TCI Provider 2 also claimed that having a precise number of the planned TCI utilization will give the management a reference to check the actual installations on site. An automated and updated TCI utilization plan is reducing the effort of inspections and the burden of proofing completed tasks on both the contractor and client-side due to better information and transparency. Having transparent information also increases safety on site. Both Consultant 1 and TCI Provider 2, expressed that, if the utilization plan of TCIs includes a safety risk factor of each TCI, construction professionals can be notified which activities need special attention due to a higher risk factor. This can be addressed in the safety meeting and its weekly look-ahead plan or the daily meeting of the contractor. Furthermore, transparent information about TCIs would allow a tidy and well-organized site maintenance with reduced safety hazards as TCIs are not lying around the construction site and one knows where they belong to.

The following simple example of Consultant 1 reveals the potential of this system in a common situation on a construction site. If a construction site needs to assemble 50 forms for erecting concrete at peak time, in common practice the site manager would roughly estimate this amount during site employment and order 50 forms. This formwork is then rented for the whole time of construction where it is stored and used alternately. In reality, 50 forms are only needed at the peak time of construction and apart from that only 30 forms are needed to facilitate the normal construction pace.

In this situation, it would be nice to tell the logistics centre of the contractor to only provide 30 forms which will constantly stay on site. As soon as the peak time is in reach, 20 more forms are delivered on site but only stay on site for the peak period. After the normal construction pace is set again, the surplus forms can be used on another construction site or returned to the supplier. This lean formwork planning and management is enabled by the proposed solution and can be expanded to all TCIs, resulting in only having the least amount of resources on a construction site and knowing exactly when each item is needed.

Site Observation Findings

During the site observation, several issues are identified and documented in **Appendix 2**. In reference to the previous findings of this chapter, the idea of considering TCIs in a simple way was investigated for each of the identified issues. The following table summarizes the positive effect, such a solution would have on the regarded construction site.

Issue	Potential
TCIs lying around at the construction site, blocking usable space and access ways.	Using location-based scheduling as a principle of planning would enable to specify specific storage areas for the TCIs that are not in use. These storage areas depend on the time and location of the next utilization. The information can be distributed to the relevant workers, as all information is accessible, providing transparency of TCI utilization.
Formwork elements that are currently not in use are piling up at the storage area.	An updated and detailed utilization plan of the formwork might enable a reinforced just-in-time delivery as well as a dynamic planning and lean management of TCIs. As a result, fewer TCIs are stored on site.
TCI quantities are based on rough estimations, leading to an inefficient supply and management of TCIs on site.	Quantities of primary TCIs are available on a detailed level for each activity throughout the project. Secondary elements that support primary TCIs can be calculated for each construction activity with the quantities and sizes of the primary TCIs.
Construction managers lack an overview of what is currently on site. Required information is obtained through labour-intensive site inspections.	A construction manager can easily compare the planned quantities of TCIs with what is installed on site, identifying missing parts. Actively tracking these items would also allow locating the required items for each construction activity if not stored properly.

Table 6: The derived potential of automated TCI planning from site observation

The benefits of an automated planning of TCIs are summarized based on the presented findings for the relevant stakeholders as follows:

Client
• Reducing efforts of site inspections to check the invoicing of contractor • Costs of the construction contract is decreasing regarding the TCI-related positions as their management is improved (lower renting costs, less waste, less occupied storage space) • Transparency in the use of TCIs on site
Contractor
• Better TCI estimation, based on a reliable calculation • Reliability of TCI planning – thus, more information to organize an efficient construction site management and fewer contingencies • Decreasing costs and time for handling TCIS as lean management is enables • Increase in efficiency of the construction process is mitigating delays, hence, the contractor can avoid fines
Supplier
• More dynamic rent system where TCIs can be dynamically moved around different construction sites as updated and transparent information about the utilization of TCIs is available for all relevant stakeholders • Early integration of TCI supplier as soon as the building model and schedule are set, providing the supplier with an active role in the process of construction planning and management

Table 7: Benefits of an automated TCI planning for the different stakeholders

Based on the regarded literature and input from experts as well as the site observation, a solution framework can be derived to accomplish the simple consideration of TCIs in construction planning and management. Here, the overall goal of implementing the proposed solution is to:

a) Automatically evaluate the building model geometry

b) Identify required TCIs to each building element of the building model by applying the rule-based algorithm

c) Link the building objects with their respective TCI-information to the building locations and schedule

d) Develop a TCI-utilization plan based on the building elements, their locations and schedule information

e) Enable passive monitoring of the TCI items with progress monitoring data

f) Visualize data automatically and interactively for all relevant stakeholders

By reflecting on the determined purpose of the proposed solution and the high-level visualization of the research frame in figure 11, the following process map further details the framework for planning and managing TCIs with the findings of this chapter. Here, it provides an overview of the whole data flow for the process of planning and managing formwork in construction. The scope includes the integration of the required raw data fom BIM, LBS and TCI as well as the data management in an open data environment which shall result in the achievement of goals a) to f). Besides that, it also outlines the role of the engineer, the contractor as well as the TCI-supplier.

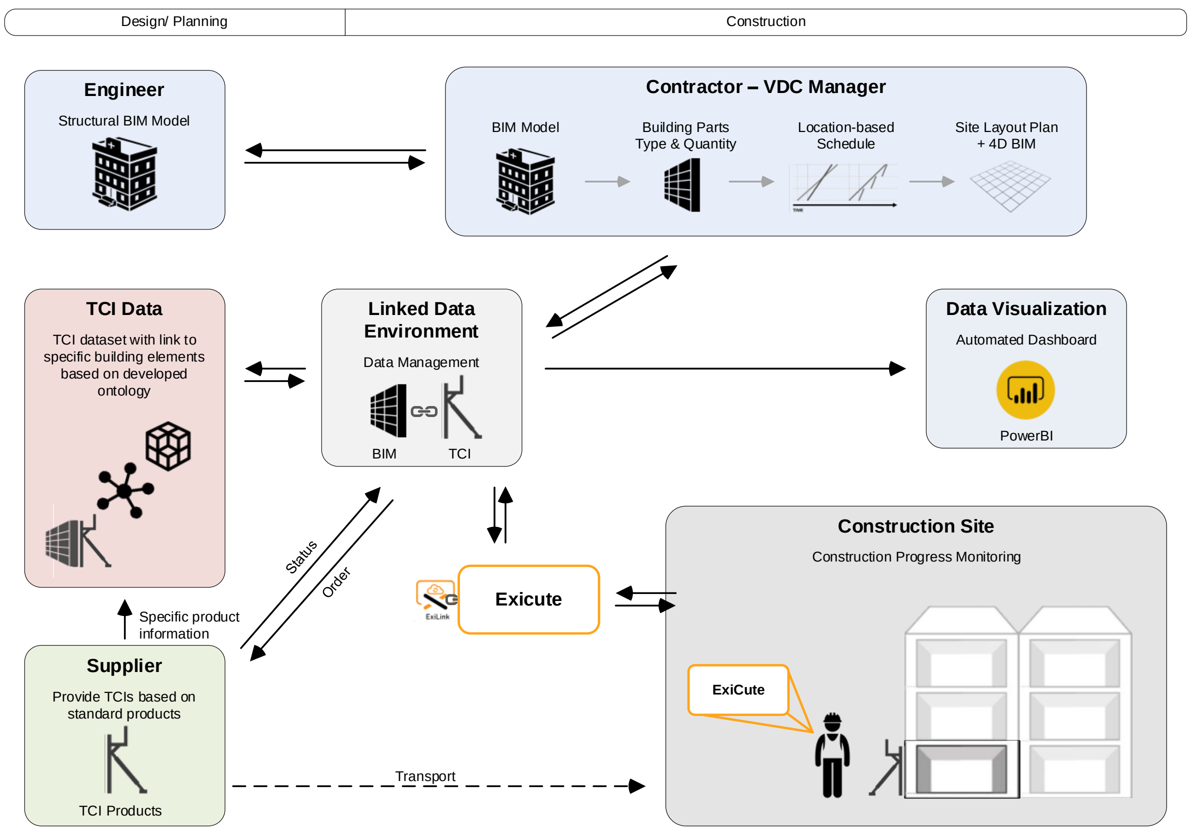


Figure 21: Proposed framework for the innovative TCI management (own visualization)

In chapter 6.1, these findings are utilized to develop a functioning system architecture of the data environment for the proposed solution framework.

5.2.2 Linked Data Environment

As shown in the proposed framework for an innovative management process of TCIs, data management is conceptualized in a Linked Data Environment. Unlike current data generation within specialized and closed software environments, Linked Data "*technologies can provide an open and common environment for sharing, integrating and linking data from different domains and data sources*" (Beetz and Zhang 2016, p. 1). In the proposed framework, this would enable to integrate BIM data with TCI information into a common data environment, crossing software-based and organizational borders. Thus, the following chapter will introduce the concept of a Linked Data Environment and further explore the benefits, it brings to the proposed solution.

The World Wide Web Consortium defines Linked Data is a *"collection of interrelated datasets on the Web"* (W3C 2015). Behind Linked Data lies the concept of creating a web of data, called semantic web, which, unlike the common web, is not only a network of documents but contains interconnected data, accessible through the web. Hereby, any kind of data can be published in the semantic web and made available in a standard format, called Resource Description Framework (RDF). RDF data is stored in a data graph that consists of triples. Triples always comprise a subject, a predicate and an object. Predicates have the power to create classes and relations within a data model in order to create a data graph. Using the semantic query language SPARQL allows to retrieve and process the data of the data graph. Through relationships, different data can be connected and processed with Semantic Web tools, thus, creating a large-scale integration of data, usable for any kind of application (W3C 2015). According to Pauwels et al. (2018), *"across industries, Linked Data is recognized as an important set of fundamental methods and technologies to address interoperability and information exchange challenges*" (Pauwels et al. 2018, p. 195). It is further explained by Pauwels et al. (2018), that especially Linked Data features like the use of URIs for data identification and a standardized data format founded on standardized ontologies with a universal query and rule languages are crucial aspects for enhancing interoperability in an industry. The benefits of this approach in several industries have also motivated researchers in the construction industry to engage in Linked Data, resolving interoperability issues of common authoring systems in BIM-based construction (Santos et al. 2017). The W3C - Linked Building Data (LBD) community group and other researchers developed ontologies to describe building information in the context of Linked Data.

As these ontologies only give a general concept of describing a building, stakeholders in the industry are encouraged to extend or develop new ontologies, aiming to eventually describe all aspects concerning construction as standardized Linked Building Data. According to the LBD community group, the use of Linked Data in the construction industry shall lead to a decentralized and integrated information infrastructure. Beetz and Zhang (2016) additionally highlight the importance of using an open data environment as Linked Data for sharing and linking construction data from different sources and domains. Integrating data in the construction industry is increasingly gaining attention and relevance and therefore, Linked data technologies to describe building data are proposed from several research projects to face this need (Beetz and Zhang 2016; Costa and Pauwels 2015; Rasmussen et al. 2019). Data, in this concept, is supposed to be created and owned by different stakeholders. For the purpose of collaboration within a project, data can be made accessible for authorized parties. In this way, integration of different disciplines is achieved by linking and providing specific data, rather than entire building models. Depending on the task in a construction project, the available datasets can be queried by applying a ruleset or a calculating algorithm in order to retrieve the required output data. By providing all required data from different stakeholders through the semantic web, engineering or construction management related tasks can be solved by simply querying and processing the project data across disciplines (Rasmussen 2018). An example of how Linked Data can be utilized in the design phase of a building project for dimensioning a heater is exemplified in figure 22. Here, a heater sizing application receives data from different stakeholders, integrates the information into a data model and applies a calculation engine in order to calculate the heater size, based on all the given requirements and inputs. Moreover, a few Linked Data principles and features are mentioned in the left side of the figure.

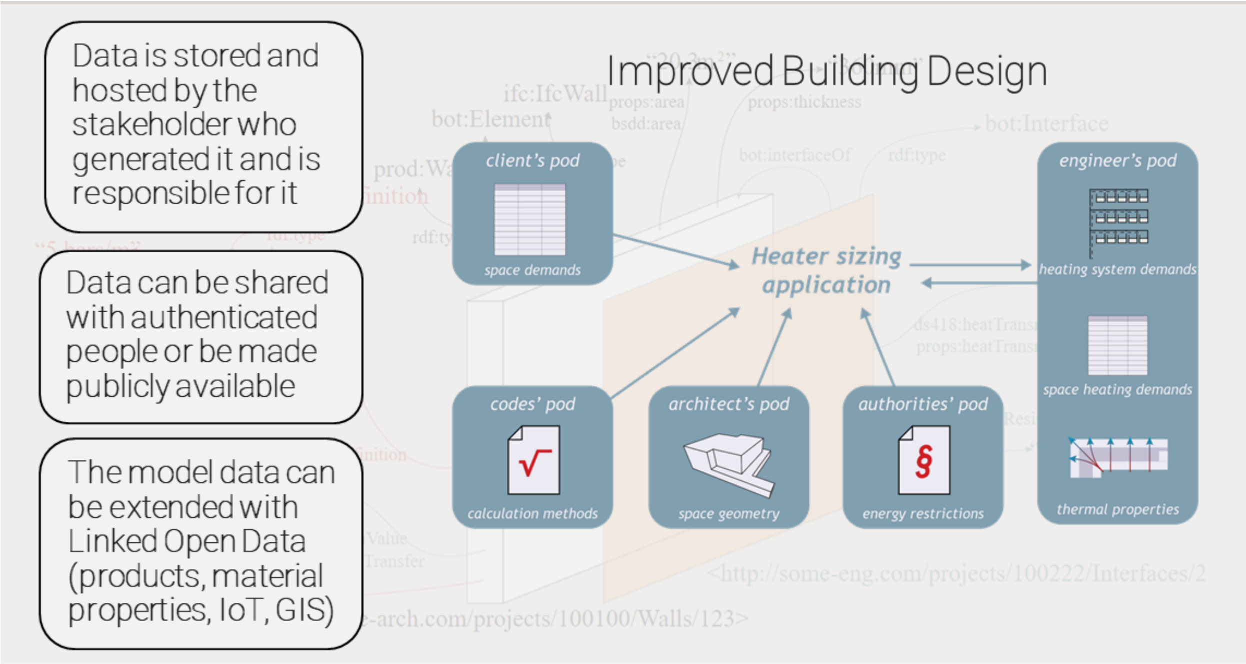


Figure 22: Linked Building Data - Heater Sizing Example (Rasmussen 3/5/2020)

Hence, the use of Linked Building Data for this specific research fits the previously identified requirements for considering TCIs in construction planning for several reasons. Firstly, it creates a common data environment and thereby, allows to link data from different construction disciplines. Secondly, the provided building data can be processed with an algorithm that creates the required knowledge to derive a TCI-utilization plan and additionally, as the data is stored in a standard and machine-readable format, the output data is suitable to be converted and further used for the purpose of data visualization. Lastly, Linked Data constitute an open data environment and therefore allows to be extended with new data from several sources, such as IoT-sensor or product catalogues.

However, to implement a Linked Data environment, a standard way of describing building data must be established across the construction industry. Hence, domain-specific and open ontologies have to be developed. As Sørensen et al. (2010) already identified ten years ago, standardized ontologies are required to "*reduce the barriers for collaboration across projects*" (Sørensen et al. 2010, p. 38). Here, it is mentioned that ontologies are playing an important role for data integration in ICT systems and thus, several ontologies have to be established to holistically describe the regarded context and serve as an industry-wide standard.

In the reviewed paper, the author is exploring different ontology types, which together fulfil "*the potential of a digital link between the virtual models and the physical components in construction*" (Sørensen et al. 2010, p. 39). The ontologies, utilized and developed for this thesis, are presented in chapter 6.1.

In conclusion, Linked Building Data (LBD) adds a lot of value as it allows to integrate TCI data into the existing BIM-based construction process, as proposed in the previous chapter. Thus, this research aims to unlock the value of LBD for the improvement of TCI planning and management in order to improve productivity and safety on construction projects.

By proposing and conceptualizing a new management process of TCIs which shall enable a simple consideration of these items in the existing BIM-based project delivery, a crucial part of **RQ2** was already answered. It was highlighted, that an improvement of the management process is only possible if TCIs are planned beforehand. Thus, the thesis proposes a concept of automatically planning TCIs and integrating the information into the existing BIM data, comprising both the building model and a location-based schedule. By then introducing the Linked Data environment which is not only providing an open and functioning data management system but also envisions completely new possibilities regarding construction project delivery, a well-balanced and innovative answer was provided for research question two.

Chapter 6: Solution Development

This chapter follows directly up on the conceptual solution that was developed in the previous chapter and approved by answering **RQ2**. Consequently, this chapter explores the realization of the proposed framework (Figure 21) by utilizing the design method prototyping in order to systematically develop a solution, fulfilling the identified goals a) – f).

As the answer to **RQ3** cannot only be derived from theoretical information, the theoretical concept must be put into practice in this process step. First, an initial prototype is developed with a small demo project. This first phase of prototyping is then continued by applying the solution to a case project and by further developing the prototype from identified findings. Based on the demo project as well as the case study findings, **RQ3** is answered. Furthermore, the developed prototype is evaluated by a diverse group of experts from the construction industry in order to validate the solution's potential and to derive limitations and further improvements. Finally, this chapter is able to answer the last research question **RQ4**, accomplishing the task of answering all sub research questions. Subsequently, the next chapter will lead to a discussion answering the main research question **RQ0** and capturing the developed solution in an integrated and lean process of managing temporary construction items.

6.1 Demo Project (Input for RQ3)

As the previous chapter revealed, automatic planning is the key to consider TCIs in a simple way in the process of construction planning and management. Furthermore, the benefits of the proposed solution are identified, improving safety and productivity on site. Thus, the following section will explore the practical development process of the identified theoretical solution in order to investigate the application in the existing process of construction.

First, prototyping (Martin and Hanington 2012) is applied as a method to develop the minimal viable product which proofs the concept of the proposed solution, according to the developed goals a) to f). Therefore, a small demo project is created which includes all the data of a real construction project in a smaller and more convenient scale. However, the scope of the demo project must be sufficient to demonstrate the functionality of the solution. A detailed documentation of the steps in the demo project is added to the appendices as **Appendix 3**.

Hence, this chapter only reflects on the main aspects and findings of the demo project, leading to the next chapters, where the prototype is tested in a real case study and is finally subject of a critical discussion where it is tried to create a framework for the prototype solution, that allows implementing the solution in a realistic context.

As described before, the existing construction project data must be integrated into a common database from which further action can take place to create a TCI-utilization plan for the project. With Linked Data, the data is converted into a structured format and hosted as an interconnected data graph. First, the required datasets of each source are developed as individual data graphs in the database and later, all data can be merged into one combined data graph in order to receive the desired results. Subsequently, these results are further used for the purpose of data visualization, aiming at distributing new knowledge to all relevant stakeholders, directly benefitting from it in their daily work. For a better understanding of the developed solution, figure 23 summarizes the system architecture of the demo project and gives an overview of the consecutive prototyping steps fulfilling goals a) to f).

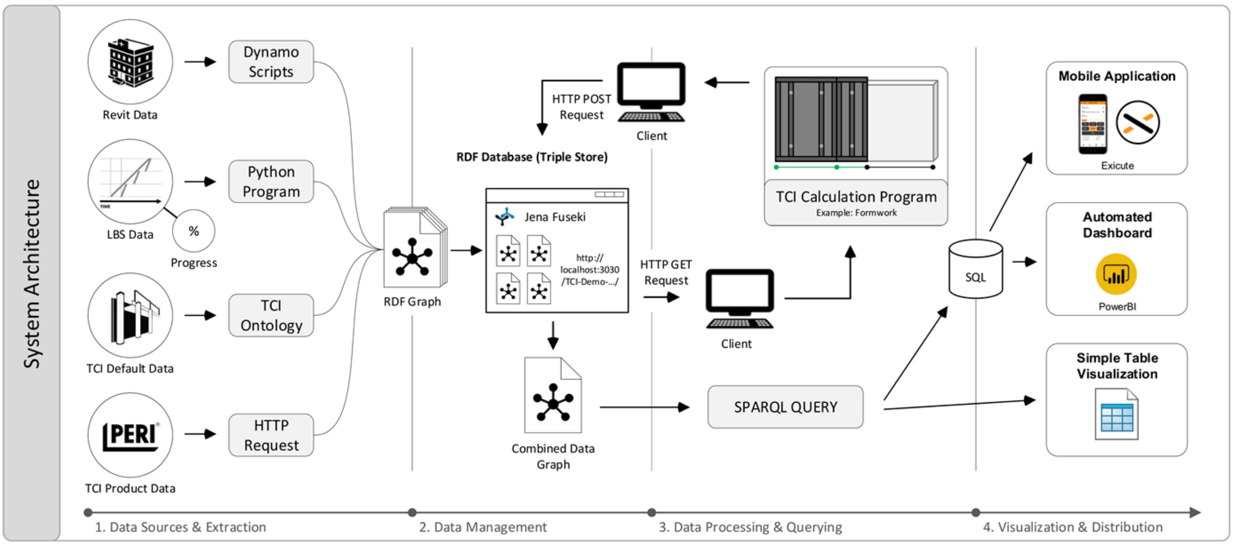


Figure 23: System architecture of the proposed solution (own visualization)

Figure 23 shows that the prototype solution is divided into four steps. These steps also represent the structure of this chapter, guiding the presentation of the prototyping steps and findings.

6.1.1 Data Sources & Extraction

For the development of the proposed solution, four main datasets are needed to deliver the raw data. Model data is providing information about the building elements and LBS data is based on a location-based schedule that contains information about each planned construction task. LBS data can be further extended with updated progress information. Thus, the three data sources model data, LBS data, and progress data can be distinguished, forming the group of data which can be extracted from any BIM-based construction project, using location-based planning. To complement the data and add TCI-related information, an additional dataset has to be established containing information of standard TCI products to quantify the TCI-demand for each building element, based on the model data of the project. In total, four datasets are generated from different sources, serving as valuable raw data for the solution. Figure 24 visualizes the different datasets and highlights the contributed information of each source.

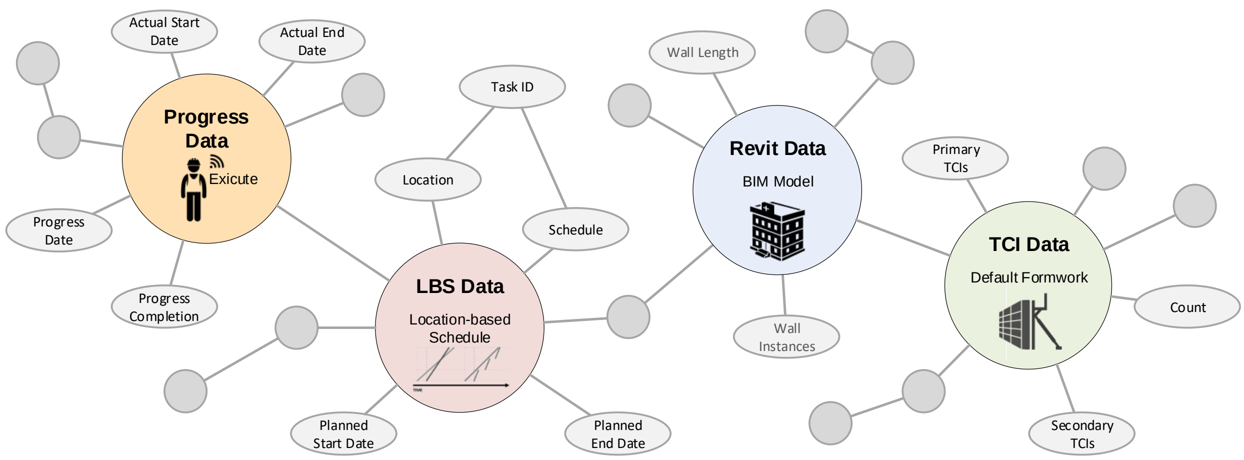


Figure 24: Datasets with contributed information (own visualization)

Each of the shown datasets is converted into an individual data graph in RDF. To describe each dataset, ontologies are created as a basis from which classes and properties are extracted to describe a data instance and its context. Hereby, the intention is to reuse existing ontologies as the Building Topology Ontology (https://w3id.org/bot#) and create new classes and properties to extend existing ontologies beyond their contextual limitations. A building element from the model data, for example, is described generally with BOT with the triple *bot:Element rdf:type owl:Class*. A wall, for instance, is defined as a subclass of a building element with *product:Wall rdfs:subClassOf bot:Element*.

In contrast, as there is no existing ontology describing the context of TCIs, new classes and properties are developed with the exemplary namespace http://test/tci/. All TCIs are summarized with the class *tci:TCI* being part of the class hierarchy in the newly created TCI ontology. The same process had to be applied to describe the LBS data with the exemplary namespace http://test/lbs/. All created ontologies are provided as part of the thesis submission and can be found in the public GitHub repository *LBD-for-TCI*, described in **Appendix 8**. In the following sections, each dataset is shortly highlighted, and the process of data extraction is explained.

Model Data

A demo project was created in the common 3D-modelling software Revit 2019 to provide small scale sample data of a building model. Dynamo scripts are then used to extract the required information from the model and convert it to RDF triples. As the demo project focuses on creating a utilization plan of vertical formwork elements, only in-situ walls are considered for the data extraction in RDF triples. However, the scale of data extraction can easily be extended. The following data graph excerpt shows one of the, in total, 14 extracted walls.

```
wallinst:450d31df-4383-4692-9be4-9c0935e083ef-0008f0ba
        a                     product:Wall , ont:Concrete400MmCastInPlace ;
        rdf:label             "(12)11.15,05.1.S1" ;
        bot:adjacentElement   wallinst:40cab1d1-1d6f-47a3-9afb-bd8c6300ff7e-0009c504 , wallinst:c1037085-1aff-4644-8770-66dc41edbf0b-0009d67e ;
        props:Element_ID      "585914" ;
        props:Revit_GUID      "450d31df-4383-4692-9be4-9c0935e083ef-0008f0ba" ;
        props:angle           0.0 ;
        props:area            19.2 ;
        props:height          3.0 ;
        props:length          6.2 ;
        props:level_simple    "Level1" .
```

Figure 25: Excerpt of the resulting model data graph (own visualization)

The property *props:Element_ID* is probably the most important information, as it identifies each building element instance with a unique identification code and is later used to link the schedule data to the model data, as the Element ID is also utilized in the scheduling system.

Location-Based Schedule (LBS)

Schedule information contains crucial data in the process of planning and monitoring items in a construction project as it provides information about when specific building objects are planned to be executed. In the construction industry, this is traditionally done with Gantt-Charts.

These schedules contain information when a task is planned to start, how long it will take and when it will end. A further development of this approach is the Location-Based Scheduling (LBS) which extends the schedule with a location dimension. Besides many proven advantages, LBS allows a continuous and efficient construction process by reducing waste (Olivieri et al. 2018). Here, the software VICO Office is used to create a BIM-integrated location-based schedule of the demo project. The software allows to extract schedule data to different JSON-files, from which the required data can be structured and converted into RDF triples. The provided data contains information about the planned schedule as well as information about the location. Furthermore, the data can be linked directly to each building element with the respective Element ID. As the prerequisites of this solution require to model the building according to the construction tasks, building elements are not split and thus, can be allocated to a single construction task.

Progress Data

In the introduction of this chapter, progress data is introduced as a possible extension of the schedule data, allowing to passively monitor TCIs with the updated progress information from the construction site. This data contains information about the actual start and end date of each construction activity as well as the percentage of task completion. Using an application of the company Exigo A/S, called Exicute, the progress information is requested from the construction site and directly transferred into the VICO schedule. Exicute is a platform that allows the construction workers to track their own work. Similar to "*Site-BIM*", presented in chapter 2.1.2, such a tool allows capturing feedback and updated information from the construction site (Davies and Harty 2013). The resulting data graph is presented as an excerpt in the following figure.

```
inst:1000.0.145882  a              lbs:CompLoid , product:Wall ;
        lbs:hasCompLoid            "1000.0.145882" ;
        lbs:hasLocation            "Lev1_loca(w)" ;
        lbs:haslocLoid             "1000.0.355001" ;
        lbs:hasschedLoid           "1000.0.321768" ;
        lbs:hastaskLoid            "1000.0.358588" ;
        lbs:taskActualEndDate      "NULL"^^xsd:dateTime ;
        lbs:taskActualStartDate    "NULL"^^xsd:dateTime ;
        lbs:taskPlannedEndDate     "2019-04-08 07:28:48.000"^^xsd:dateTime ;
        lbs:taskPlannedStartDate   "2019-04-04 11:00:00.000"^^xsd:dateTime ;
        lbs:taskProgressCompletion "0.0"^^xsd:nonNegativeInteger ;
        lbs:taskProgressDate       "NULL"^^xsd:dateTime ;
        props:Element_ID           "585914" ;
        props:Revit_GUID           "450d31df-4383-4692-9be4-9c0935e083ef-0008f0ba" .
```

Figure 26: Excerpt of the resulting LBS data graph (own visualization)

TCI Data

The last dataset is comprising crucial information for the consideration of TCIs in construction, as it describes a set of TCI elements, which is used to calculate a the TCI demand for the project. In this case, a new ontology is created, describing a the context of formwork utilization. Based on this standardized ontology, a data graph is developed, containing information of a default set of formwork elements as interlinked RDF data. The information in the data graph is later used to quantify the amount and kind of TCIs for each building element. The following figure is presenting the individual TCI types of the default formwork set with their specific dimensions.

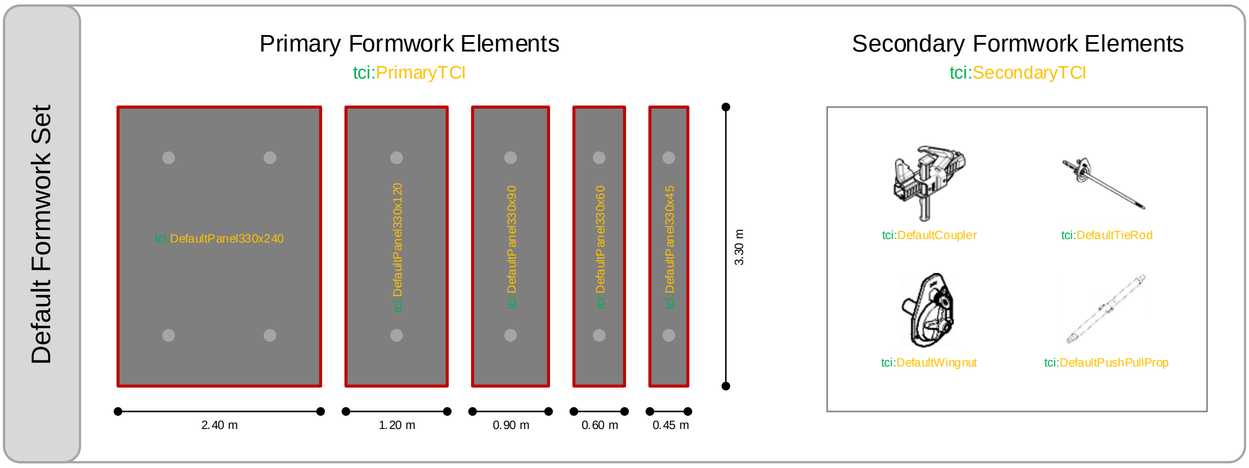


Figure 27: Default Formwork Set (own visualization)

Besides default TCI sets, the proposed solution must also allow to include specific product information as soon as a specific supplier is selected in the project. Hence, the default solution is supposed to give the relevant stakeholders a general overview of the TCI utilization on the construction site, which is later further detailed with specific product information of products that are actually used on site. The resulting TCI utilization plan will then represent exactly what is supposed to happen on site and thus, has the same level of detail as a location-based construction schedule would provide for permanent building items as slabs and walls. In this demo project, an exemplary dataset was derived from a product catalogue of the formwork solution PERI MAXIMO MX15 (PERI GmbH 2020). Although the dataset is not applied to the demo project, the creation of product catalogue with RDF triples reveals the possibility to update the formwork consideration with real product information.

A further consideration within the TCI data was to enhance the safety awareness of the construction workers by adding a Safety Risk Factor (SRF) to every TCI that is used in a specific task. The average SRF of all TCIs in one task can provide valuable insights into the safety risk which the construction workers are exposed to when executing a specific task. In this way, the construction workers can prepare and raise safety awareness at those highlighted tasks. Based on safety guidelines which are presented in chapter 5.1 the SRF for the developed prototype is determined in the range LOW, MODERATE, HIGH, indicating safe and unsafe operations. In this prototype, it is derived by the size of the formwork panels as it is assumed that this factor mainly drives the safety risk. The presented SRF is the same for all similar types of formwork, meaning that initially, there is no difference in their safety risk. However, the individual assessment of a specific product may change the SRF based on the utilization specifications. Applying additional safety means to the formwork operation will increase the SRF. Generally, the utilization of an SRF to label and visualize risky tasks is considered a valuable input in this prototype to raise the safety awareness of the construction workers. However, this SRF is currently only based on a qualitative consideration from a theoretical guideline and assumptions and must be continuously futher developed with the feedback of the construction workers. In order to summarize this chapter, table 8 is providing information on all datasets and how the prototype is utilizing the data.

Dataset	Source/ File	Extraction	Gained Information
Model Data	Revit (rvt.)	Dynamo, Javascript HTTP request	• Wall instances with ID codes • Geometry (length, height, width, area) • Wall orientation • Adjacent walls on the same level
LBS Data	VICO Office (.vico)	JSON transfer, Javascript program	• Wall instances with ID codes • Schedule, Location, Task ID • Location Information • Schedule Information (Planned) • Progress Information (Actual + Progress)
TCI Data	New Ontology based on formwork product	New Ontology, created in protégé	• Classes/ properties describing formwork • Formwork instance information • Installation/ Dismantling time • Safety-Risk Factor (SRF) • Product state (Assumed, Confirmed) • Cost information (Monthly Rent)

Table 8: Summary table of data generation

6.1.2 Data Management

In chapter 5.2.2 the Linked Data environment was introduced, utilized by the proposed solution to manage the extracted data, process it and provide access for further utilization. Generally, Linked Data is stored in a database called triple store which is accessible through a simple HTTP request. The storage system, used for this prototype, is operating through the URL namespace http://localhost:3030/ which allows communication to receive or send information. Usually, Linked Data principles suggest publishing data openly, but as project information in the construction industry is mostly confidential, an authentication system is required to only give access to relevant stakeholders. Although creating this security point limits the accessibility to the data in the triple store, it does not affect the possibility to gain data from all Linked Open Data knowledge graphs as this data is available in the semantic web through simple URIs. Data in a triple store can either be queried directly through the interface, using the SPARQL query language or for more advanced data processing, the data can be accessed through a SPARQL query over HTTP request on the SPARQL endpoint URL, which allows to receive queried data, process it in a program and write it back to the triple store (Gearon et al. 2013). This working principle is also utilized in this prototype, visualized in the system architecture (cf. Figure 23) and explored in the next chapter.

6.1.3 Data Processing & Querying

In this step of the prototyping, all necessary data is generated and stored in a structured and accessible format. In order to create knowledge from this data, the data has to be linked together by applying a rule-based calculation tool. As SPARQL queries are quite limited in their functionality, small programs in Javascript were developed for advanced data processing. In this case, two links have to be created. One, linking the model data with the LBS data by developing a program that combines the datasets through their common ID code "*Element ID*", identifying each wall instance. The second link creates the relation between the model data and the TCI data and thus, incorporates the task of calculating the formwork quantities for each wall instance. As the purpose of the prototype is not the development of an advanced formwork calculation program but rather to prove the concept of an automatic TCI planning, some simplifications to the calculating algorithm are applied, which can be found in the documentation (**Appendix 3**).

The following visualizations present first the data sources, which are used in the calculation engine and subsequently explore the workflow of the applied algorithm to calculate the formwork layout for each wall instance.

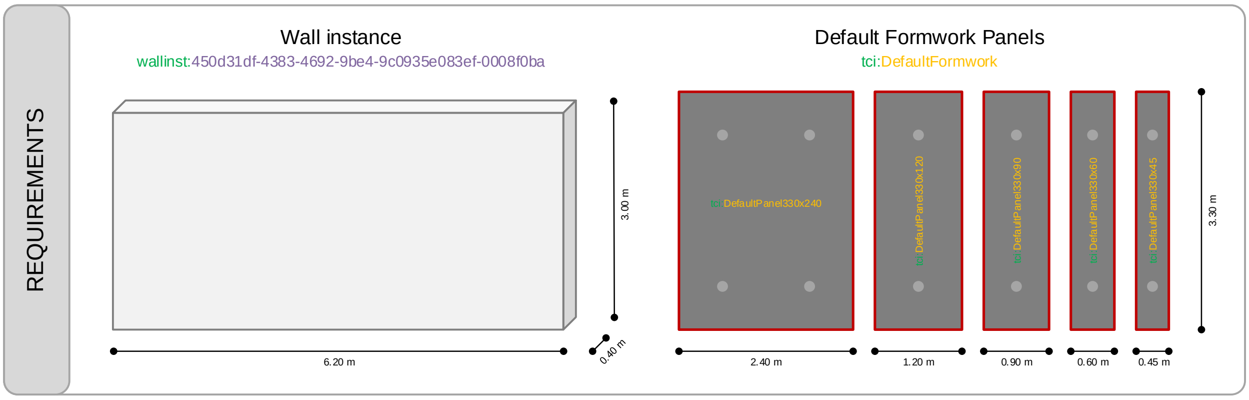


Figure 28: Data input for calculating the formwork demands (own visualization)

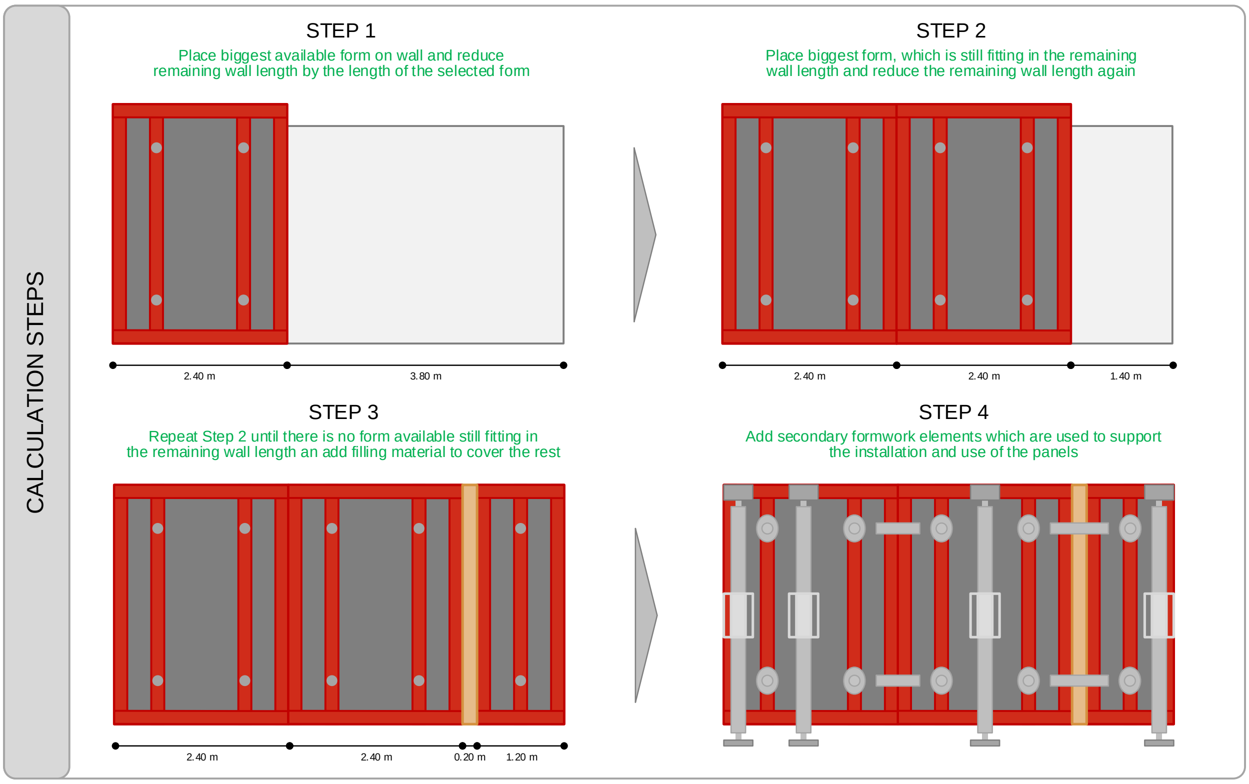
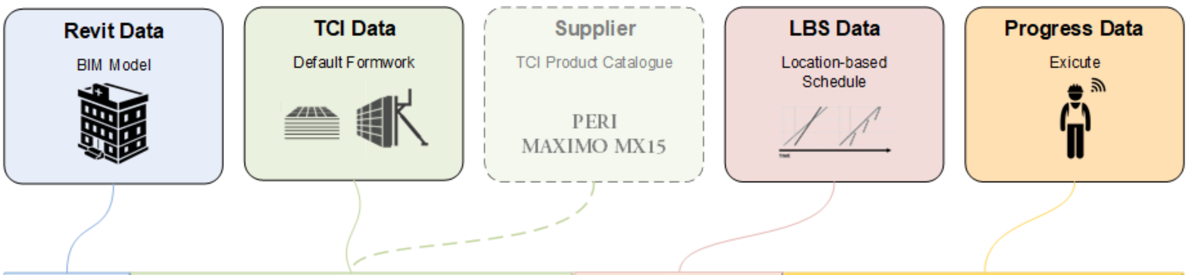


Figure 29: Consecutive steps of the formwork calculation (own visualization)

After writing the result of the program back to the triple store, the individual datasets are combined into one rich data graph, forming the basis for the TCI utilization plan. Considering only the presentation of the raw data, a SPARQL query is used to query the combined data graph and display the basic information of the TCI utilization. Figure 30 shows the output table with the considered parameters and their data source.



Revit		TCI					VICO		Exicute			
ElementID	props: length	Primary Formwork	Count	props: length	Secondary Formwork	Count	taskPlanned StartDate	taskPlanned EndDate	taskProgress Date	taskProgress Completion	taskActual StartDate	taskActual EndDate
string	*m*	*string*	*integer*	*m*	*string*	*integer*	*DateTime*	*DateTime*	*DateTime*	*%*	*DateTime*	*DateTime*
585914	6.20	Default Panel 330x240	4	2.40	Default Wingnut	12	2019-04-04 11:00	2019-04-08 07:28	2019-04-06 11:00	70.0	2019-04-04 11:00	NULL
		Default Panel 330x120	2	1.20	Default Tie Rod	12						
		Wooden filling material	2	0.20	Default Coupler	16						
					Default PushPull Prop	6						
					Default Waler	0						
644734	6.20	Default Panel 330x240	4	2.40	Default Wingnut	12	2019-04-08 07:28	2019-04-09 11:57	2019-04-08 16:00	100.0	2019-04-08 11:00	2019-04-08 16:00
		Default Panel 330x120	2	1.20	Default Tie Rod	12						
		Wooden filling material	2	0.20	Default Coupler	16						
					Default PushPull Prop	6						
					Default Waler	0						

Figure 30: Output table using a SPARQL Query (own visualization)

6.1.4 Data Visualization and Distribution

Data visualization and distribution, forming the last step in the prototype development, is a crucial part of the proposed solution as it creates the link between the theoretical consideration of TCIs in the data perspective and the physical construction project which is executed on a construction site. In this case, data visualization is the task of bringing the right amount and type of data to the specific target group in the most convenient and accessible way. Hereby, aspects of Ratajczak et al. (2018) are taken into consideration for the development of the visualization tool, as the paper proposes an interactive and web-based dashboard application for performance monitoring and lean project delivery, thus, fitting perfectly to the application of the prototype.

Since the output data in the proposed solution is stored as RDF-triples in an accessible triple store, there are several options on how to visualize the data. For the application in this thesis project, two tools are explored which shall cover data visualization and distribution to all relevant stakeholders. The first tool is a Power BI dashboard that is directly linked to a SQL database and receives updated schedule information through Exicute, the progress monitoring application of Exigo A/S. As a second visualization tool, a new tab in the Exicute application is intended to display the TCI demand for each specific construction task. The former aims at visualizing the data for the management perspective, giving a general overview of the TCI utilization as well as cost information and important KPIs, the latter at providing the contractor on site with updated TCI information for each upcoming construction task.

In order to use the data in both visualization tools, a data conversion to SQL is required. This is being done again with a Javascript program that accesses the triple store, receives the required data with a SPARQL query, converts the data into a SQL query and writes it directly to an existing SQL database. In this process, several SQL tables are created which represent the output data of the TCI-utilization plan and are used to apply the data to the selected visualization tools. The following two figures represent static example screenshots of both tools. More information can be found in the documentation of the demo project.

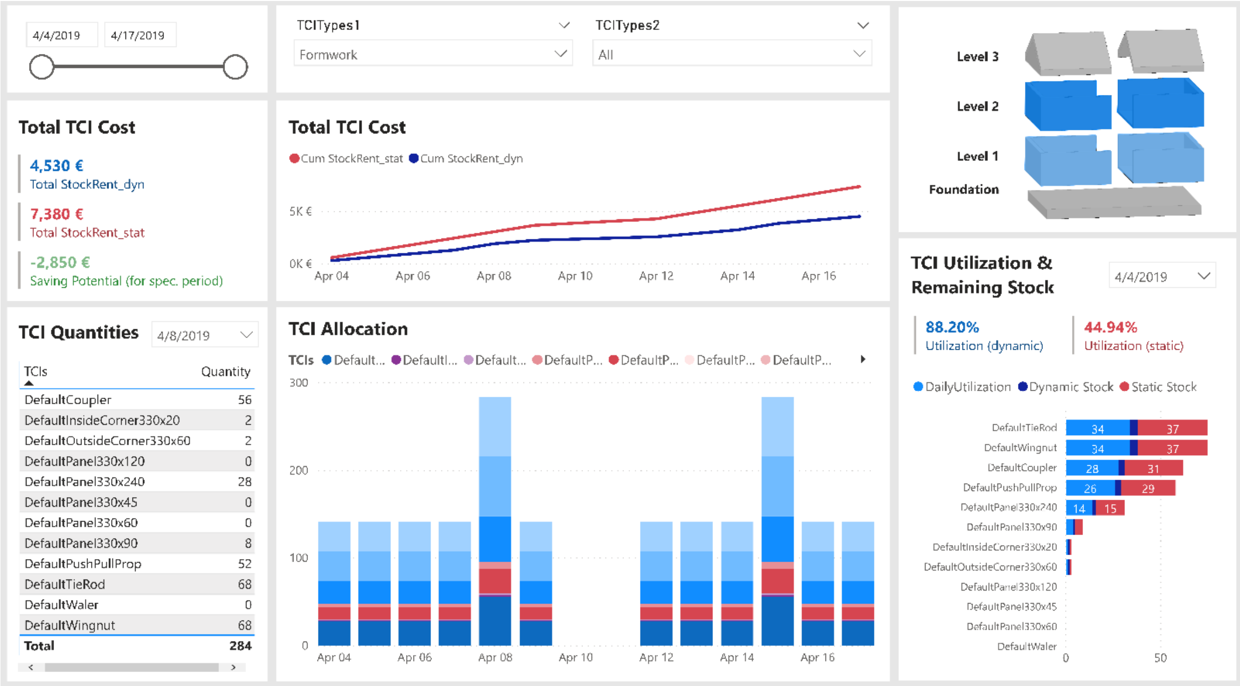


Figure 31: Visualization Tool 1 - Power BI Dashboard *TCI Utilization* (own visualization)

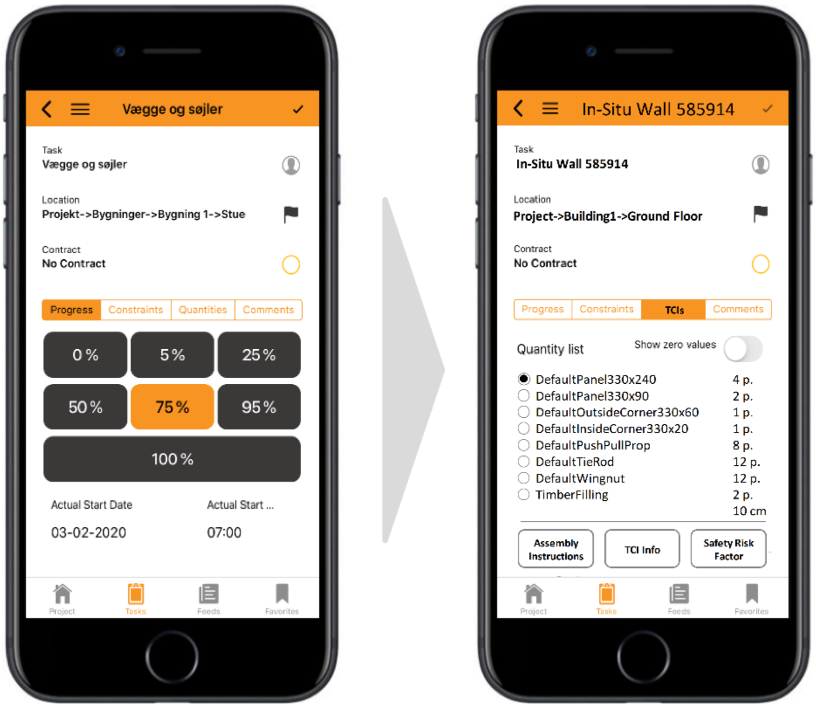


Figure 32: Visualization Tool 2 - New tab in Exicute application (own visualization)

Concluding the demo project, the process flow of formwork utilization, which was introduced in chapter 5.1 in figure 19 is revised with the gained results of the developed prototype solution. A resulting and revised version of the process flow shall capture the entire scope of the developed solution and display each consecutive step of a lean and integrated management process of formwork that is enabled by the proposed solution. The revised process flow in figure 33 is based on Kim and Teizer (2014) and summarizes the different levels of planning and managing formwork elements with the solution in the three flow charts for estimating, controlling and managing formwork. Furthermore, the flow charts highlight the process outcomes of the prototype in each step, where the developed solution is adding value to the construction process. Therefore, the highlighted outcomes form the main part of the data visualization and are distributed as valuable information to all relevant stakeholders. The visualized process outcomes are coloured in yellow for the dashboard and orange if they are used in the Exicute application.

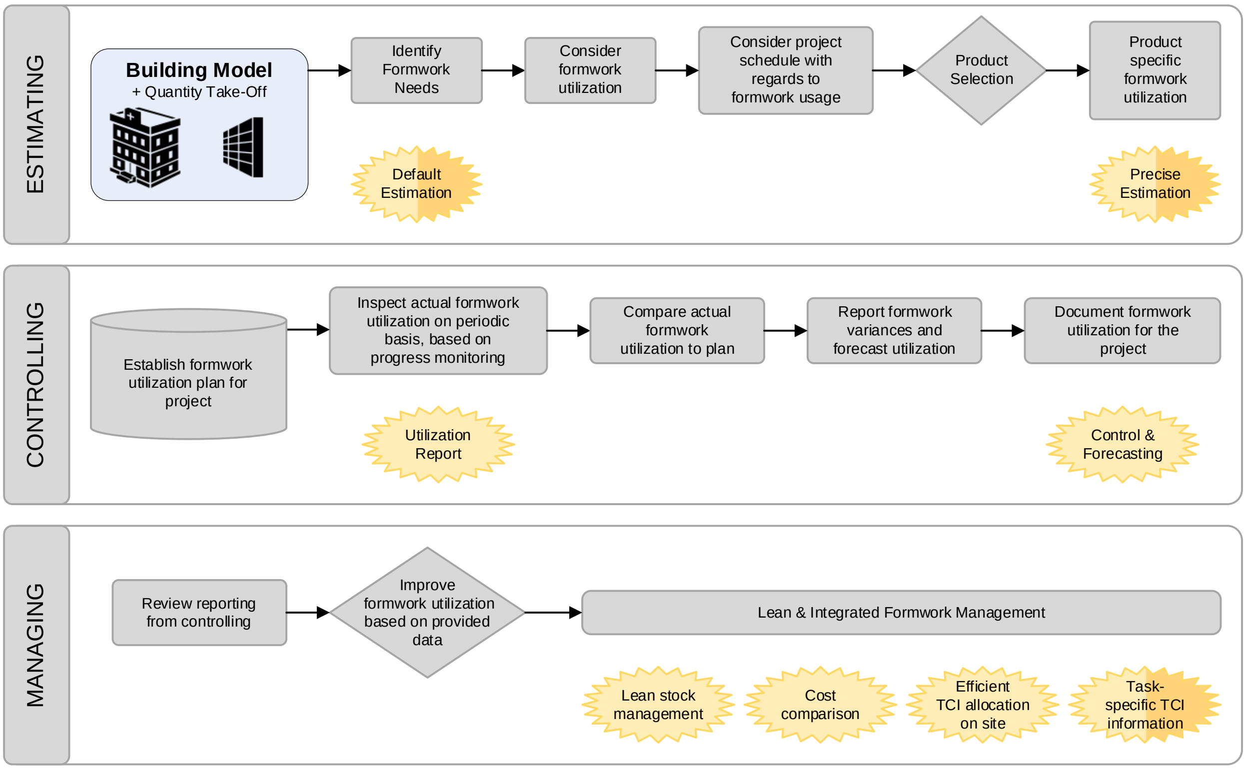


Figure 33: Revised process flow the formwork utilization (own visualization)

6.2 Case Study (Answering RQ3)

The case study is part of the prototyping process of the proposed solution and continues the development of the previous chapter. As a real case application of the proposed solution, the conducted case study aims at exploring the utilization of the improved process of TCI planning and management in a big scale construction project. By applying the prototype now on a case project, the case study will further prove the concept and functionality of the developed prototype. During this application, the prototype is further developed and adjusted to fit the needs of a real construction project. These developments and modifications will be documented in chapter 6.2.2. Furthermore, the case study tries to identify limitations and required improvements regarding the developed solution, which will then help to reflect on its current level of development. This information is subsequently integrated into the creation of an interview guide, that is utilized in the next chapter, where the solution is evaluated by 12 experts from the Danish construction industry.

Similar to the previous chapter, a detailed documentation of the case study is added to the appendices as **Appendix 4** and all files are included in the GitHub repository (cf. **Appendix 8**). While the first sub-chapter introduces the case project and additionally validates the earlier defined prototype simplifications, the second part follows with a presentation of the different steps in conducting the case study and further developing the solution. In the end, an objective reflection upon the prototype solution and the findings from the case application concludes the case study. This chapter follows the same order as the detailed documentation in **Appendix 4** and is highlighting the main aspects and key findings of the case study.

6.2.1 Case Study Project

The case study is based on a public construction project of a new healthcare science faculty. The project has a gross area of 50.740 m² and consists of six different building sections which are numbered from 45.1 to 45.6 (cf. Figure 34). The interesting part of the project for this case study is located in the basement areas of building section 45.1 and 45.6 as in-situ concrete walls are applied as structural elements. Here, the developed solution is applied to automatically plan the formwork demand of the project and develop a time and location-based TCI utilization plan for the case project. Figure 35 helps to locate these in-situ walls in the building model context.

Figure 34: Orthographic picture with project sections (own visualization)

After analysing the building model in Revit and the location-based schedule in VICO Office, the simplifications that are developed for the prototype in the demo project are validated and adjusted to the current development of the solution as well as the specifications of the case project. Apart from one case, all the simplifications are still valid and therefore the developed solution is assumed to be applicable to the case study. The only simplification which is not valid in the case project is based on the building model. The solution requires the model data to be aligned to the process of construction, meaning that a location manager in the location-based schedule will not cut a wall into two as a result of the wall being modelled too big and not fitting in the location system of the project. However, exactly this issue was experienced in the provided VICO project. Therefore, the calculated formwork elements cannot be linked to a single element instance from VICO, containing task and time information. This means that two schedule tasks are applied to one wall of the building model and therefore, the formwork elements also occur twice in the TCI utilization plan. In the case project, this issue was identified in five cases, where the wall reaches over two locations of the location system. However, as this issue only concerns a small number of walls, the overall result is still regarded as valid. The issue is again mentioned in chapter 6.2.3. Furthermore, one simplification became obsolete due to the further development of the solution. This was the case for the simplification stating that corner elements are not considered in the prototype solution as the solution was further developed based on the demo project findings.

In the current development of the prototype, the solution is able to identify if a wall has a corner and applies the required formwork corner elements accordingly. This allows generating a more holistic and realistic formwork layout which benefits the reliability and acceptability of the generated TCI utilization plan (cf. Figure 36).

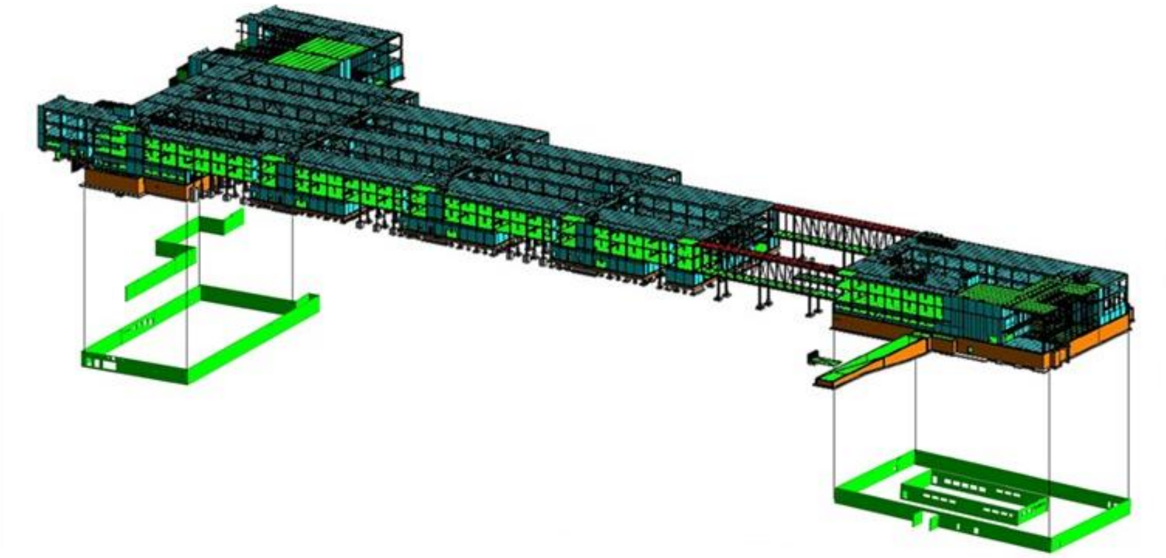


Figure 35: Revit model of the case project with the regarded in-situ walls (own visualization)

6.2.2 Case Application

This chapter now shortly explores all the different steps of the case application and highlights the new developments of the prototype which were required by and integrated during the case study. Hereby, the chapter follows the same order of the data value chain as the previous chapter already used to develop the prototype. The created system architecture from figure 23 is incorporating as its structural layout. In the first part, *Data Sources & Extraction*, only one major deviation in comparison to the demo project was applied. Both the TCI dataset as well as the Revit dataset are developed and used in a similar way. On the one hand, the formwork panel height in the TCI dataset is changed from 3.30 m to 2.70 m and two panels are stacked on top of each other to cover the wall height range of the case project. As the solution still only considers the formwork calculation in one dimension (length), this manual adjustment was needed to receive the accurate formwork layout for the given wall structures. On the other hand, the Revit data is extracted with similar Dynamo scripts, only that the new scripts consider not solely one wall type, but all in-situ wall types that are regarded in the case study.

Hence, the only remaining dataset extraction that is fundamentally changed here, is the LBS data. More precisely, the process of extracting data from VICO office was automated entirely in order to handle the huge schedule-related data of the case project.

For the automated extraction of the data and the transfer to the triple store in RDF, a program had to be developed that is able to access the data from the VICO Office file, brings it into a convenient structure, allowing to link the schedule data to the Revit data by using the wall instances and finally converts the structured schedule data into RDF triples to create the LBS data graph. As the process of developing this program was quite complex, a detailed explanation of how the Python-program works is incorporated into the case study documentation (**Appendix 4**). In summary, the developed program first extracts the data from different datasets of the VICO project and subsequently combines the information about the scheduled tasks, the location as well as the building elements that are contained in each task, into one database in SQL. After structuring all the required data in SQL, another program can easily access the data and write it into the triple store by converting the data into RDF triples.

In terms of data management, the case study uses the same open data methodology in a Linked Data triple store that was already introduced and utilized in the demo project. Therefore, the next paragraph is focusing on exploring the steps of data processing and visualization of the case application.

Above, it was already mentioned that the formwork calculation engine is only slightly modified to the requirements of the case project and further developed to also consider corner elements. Similar to the demo project, the engine takes into account the two datasets of the building model and the formwork elements and calculates the formwork demand for each of the given wall instances, based on their geometry. The resulting data is then written back to the triple store, where all datasets can then be combined into one rich dataset, containing sufficient information for creating a formwork utilization plan, ready for data visualization and distribution. The following figure shows the result of the automatic formwork planning for one wall structure in the project and by that demonstrates the functionality of creating a holistic formwork layout.

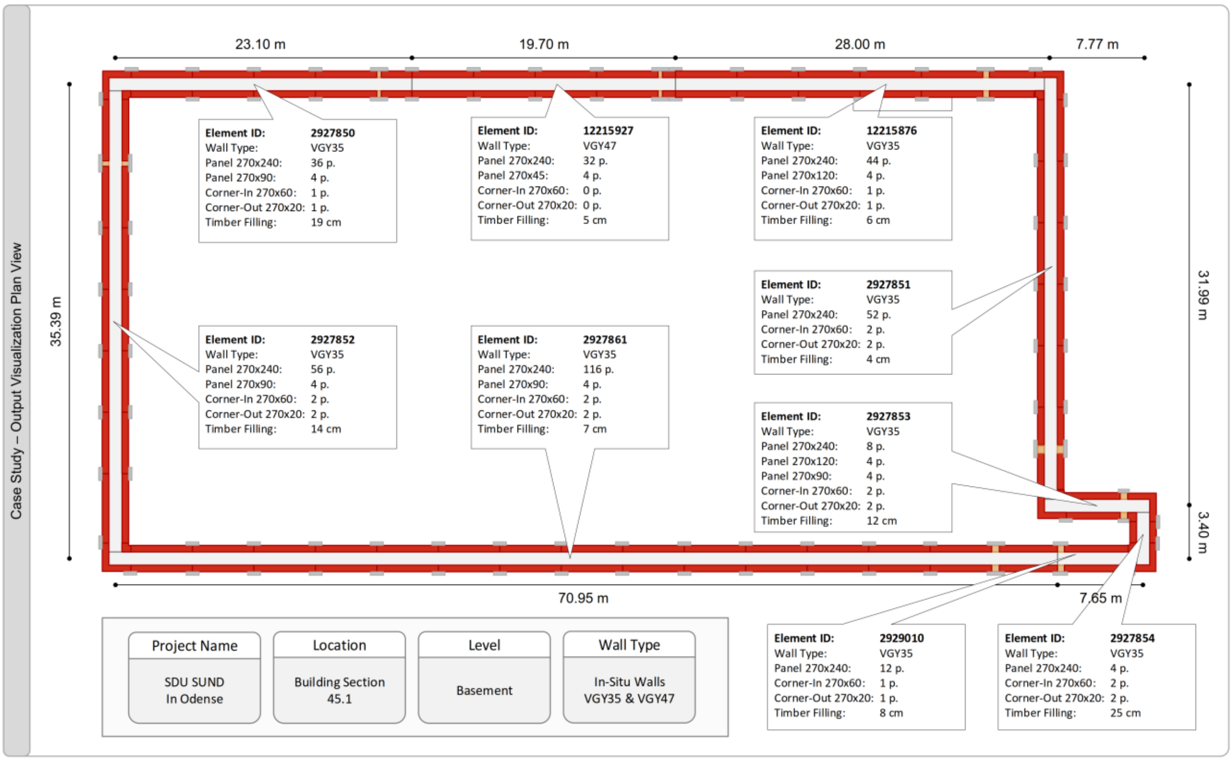


Figure 36: Output visualization plan view (own visualization)

As the final step of the case application, the raw data is upgraded to a more understandable form by visualizing the information regarding the TCI utilization plan. In contrast to the Power BI dashboard (cf. **Appendix 8**), which was further improved during the case study, the Exicute extension has not been developed over the concept level. However, the concept is already regarded as a powerful tool to visualize the TCI utilization plan in a simple and task-based format, bringing the information directly to the construction workers via the mobile application. Furthermore, the importance of bringing the data to the construction site in a mobile application was already mentioned in the state of art review and further highlighted in expert interviews. Hence, the potential of utilizing the Exicute platform to also contain TCI data is validated and is subject to further developments regarding the developed prototype solution.

Nevertheless, the main focus of the case application was to evaluate the functionality to use the developed dashboard for a big scale construction project and further develop its content to give the management of a contractor transparency and control over the utilization of formwork elements.

Summarizing this further development, the new dashboard version structures the valuable data into three pages and also gives an overview of the regarded project. The following list provides all the features, the new dashboard incorporates to visualize the TCI utilization plan while figure 37 illustrates the main page of the dashboard.

- Project overview and dashboard content
- Exploded building view of building model divided by its location management system allowing to select specific locations
- Time slicer to specify the regarded period or specific date
- Selection tool to specify the specific TCI type to be reviewed in the dashboard
- TCI Allocation graph showing the quantities of the TCI utilization on a time axis
- Comparison between static stock and dynamic stock (Static stock is calculated with the peak amount of TCI demand in the project and dynamic stock is representing the actual TCI demand with a buffer of 10%, that is enabled with the proposed solution)
- Graph showing an accumulated cost comparison of TCIs on the construction site, based on the comparison between the static stock and dynamic stock.
- List of all TCIs used in the project
- List of all PCIs (permanent building parts) which are constructed in the project and supported by the TCIs during the construction activities
- Gantt-Diagram, showing each task and its linked TCI information as well as the status of task completion (if received from the construction site)

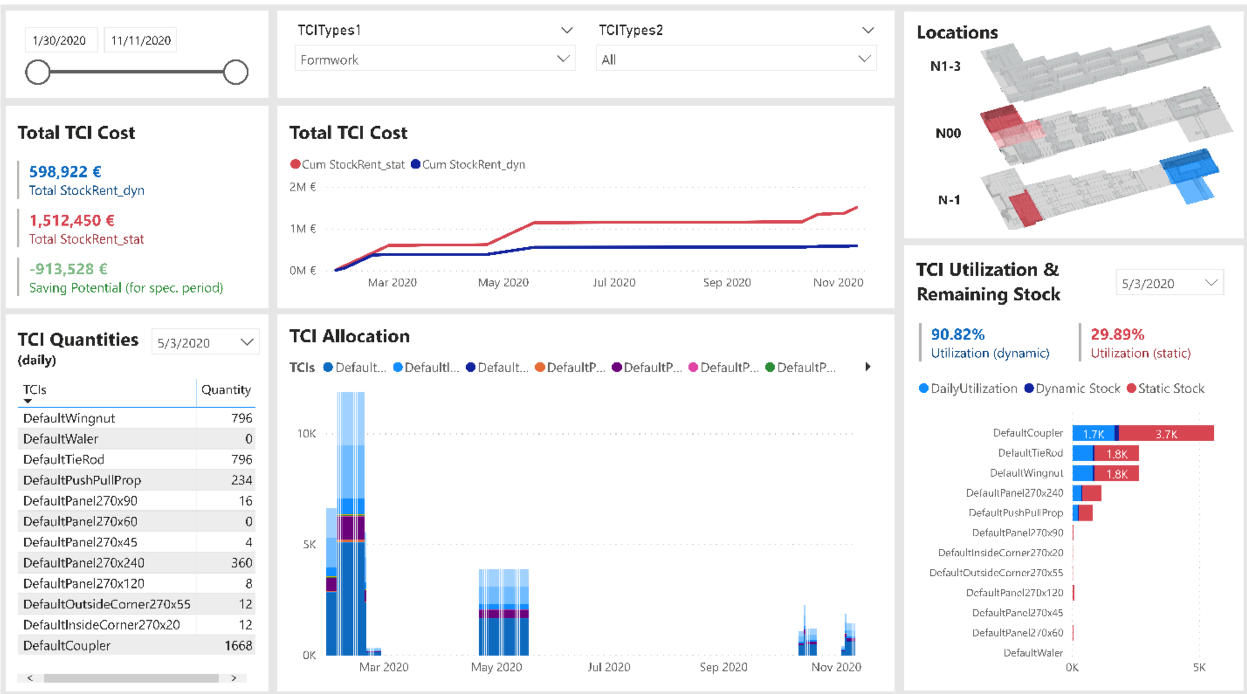


Figure 37: Dashboard Page 3 – *TCI Utilization* (own visualization)

A more detailed explanation of the entire dashboard is covered in **Appendix 4**.

6.2.3 Reflection on Case Study Findings

In this chapter, the case study findings are reflected objectively in order to draw a conclusion on the current development of the prototype and identify limitations and further needs for improvement.

In general, the case study has proven that the developed prototype is applicable also in a big scale construction project. Thus, the second phase of prototyping a solution that is able to automatically plan formwork elements and generate a location and time-based utilization plan is considered to be completed. This would also justify further development of the prototype which would finally lead to a real product or service that can be implemented in the construction industry in order to improve productivity and safety on construction sites. In this thesis project, however, the development process terminates here as the next part of the thesis focuses on the evaluation of the proposed solution from the perspective of several experts. Based on the case study findings, several limitations and issues were also identified, leading to suggestions where the prototype still maintains space for improvement. A list of the three main issues is provided below, while the case study documentation in **Appendix 4** contains a full record of the determined limitations.

- The solution is currently not able to consider the sequence of the formwork cycle and therefore, does not consider a realistic wall ending for the open side of a wall structure. In a realistic situation, plywood and walers are mounted to an open end of the wall-formwork structure in order to prevent the concrete from pouring out. This has to be considered in the further development of the prototype.

- Corner elements in the formwork application depend directly on the wall thickness of the regarded wall as this determines how much space the corner takes up of the remaining wall length. Based on this remaining length, the straight formwork panels are calculated. As the wall thickness of the regarded wall types in the solution are set manually in the calculation program and are not flexibly changed according to which walls are currently processed, the formwork layout for a minority of walls in the case project is slightly incorrect. Further development should enable the calculation engine of the solution to flexibly adjust the corner calculation based on the individual and given wall thickness.

- As already mentioned in chapter 6.2.1, the solution assumes that the modelled wall geometries are aligned with the construction process, meaning that the location system in VICO does not cut a wall because the wall is not modelled accurately according to the construction process. This limitation must be addressed in the early stages of a project to ensure that the model meets the requirements for using the solution. An alternative to the early quality assurance of the model is that the contractor adjusts the model when the location-based schedule is generated from the building model in the VDC process.

Concluding this chapter with the reflection on the case study findings, and by that terminating both the demo project as well as the case study, enough validated input is generated in order to answer research question three. **RQ3** required to explore and develop a solution that enables a data integration of TCI-information into the existing BIM process to create value for the project. As a result of this derived objective, the prototype solution was first developed on the basis of the demo project and subsequently applied on a big scale project to validate its functionality for the construction industry. The developed solution, on the one hand, is able to automatically plan TCIs by combining TCI information with the already existing model and schedule data from common BIM-tools and on the other hand, the solution provides the construction site with a TCI utilization plan that not only generates transparency over the utilization of items that are currently not considered in that level of detail but also gives the site manager the control to better plan and manage the construction site with the consideration of TCIs. Moreover, the solution proposes two different tools to visualize the data and distribute it to the relevant stakeholders who are in need of the created information. The extended use of the mobile application Exicute addresses the needs of the construction workers on site who receive a simple checklist of TCI quantities per task. The management of the contractor is benefitting from the second visualization tool – the dashboard. Here, a highly valuable set of information is displayed in a three-folded and interactive report that is directly linked to the Linked Data environment and gives the user insights and transparency over the TCI utilization for the construction project.

In conclusion, both the *Implement* as well as *Capture* part of **RQ3**, are sufficiently answered by the development of the prototype solution. Hence, the next chapter covers the input for answering the last research question, aiming to evaluate the developed solution and by that prove its potential for the construction industry.

6.3 Evaluation Interviews (Answering RQ4)

After successfully developing the prototype solution and applying it to a case project, three out of four research questions are already answered, leading the way towards the accomplishment of the **research objective**. In this chapter, the next step of the solution development is approached by evaluating and approving the prototype with the technical and managerial knowledge of industry experts.

As already introduced in the methodology chapter of this thesis, a total of 12 interviews were conducted with different stakeholders from the Danish construction industry. In the following section, the main findings of the evaluation interviews are first summarized in table format with reference to the respective interviewees, claiming each finding. Subsequently, the interview findings are presented more in detail by ordering the findings in accordance with the developed categories. Here, only a summary of all findings is provided while **Appendix 6.4** contains all findings, structured by categories. **Appendix 6.3** furthermore reveals the raw content of the interviews by displaying the summarized answers of all interviewees to all interview questions.

Before the interview content has been structured by categories, the deductively developed categories (cf. Figure 14) were further developed with the gained knowledge of the interviews. This process of inductively adjusting the categories resulted in additional categories. First, a general category was added to both groups *Benefits* and *Evaluation* in order to cover the findings which are not directly related to the previously developed categories but provide great value for the evaluation of the prototype. Moreover, the categories *Active Tracking with IoT-Sensors*, *Scalability of the solution for other TCIs* and *Integration to Site Planning & Management* are included in the *Evaluation* group. These categories aim to give a broader insight into the different aspect of further developing the prototype. Finally, the group *Business Model* was split up in two parts. One, exploring the *Integration in Existing Project Delivery*, meaning the implementation of the developed solution in the current industry and the other, focusing on the development of a *New Project Delivery System*, aiming at exploring the future vision of utilizing the Linked Data framework for establishing a new and more integrated way of delivering construction projects. While the current chapter is first presenting the interview findings, the two considerations in the *Business Model* group will be a central part of the discussion in the next chapter of this thesis.

6.3.1 Main Findings

The following table is providing an overview of the main findings, analysed, and derived from the interview data. These findings were selected as most of the interviewees agree on the respective statements or their value is considered important to be addressed as a main finding.

Main Findings	#	Interviewees
11 out of 12 interviewees agreed that the solution presents a good way to bridge design and construction by using an integrated data environment and bringing the existing data in a suitable format to the site, where both site planning and management can benefit from the improved control and transparency of the TCI utilization, leading to a more lean and safer management of the construction site	11	Client 1, TCI provider 1, Contractor 1, 3, 4, Consultant 2, 3, 4, 5, 6, 7
Importance of TCI Consideration: Contractor and TCI provider addressed the importance of integrating TCIs into the planning and management effort of a construction project as they significantly impact time, costs and quality of a project and a proper planning and management allows to reduce waste on site → Better planning and transparency benefit all parties involved in a project	5	TCI provider 1, Contractor 1, 2, 3, 4
Data Integration as Niche Solution: Automatic generation of the TCI utilization plan by using and integrating existing project data is targeting a niche in construction which is not yet fully optimized	7	Client 1, Contractor 4, Consultant 3, 4, 5, 6, 7
Data Modelling: The approach of developing a data model for each construction project and use it for calculations and generating value along the project development (for the whole life-cycle of a building) has a big potential and can be applied to many different areas, not only for formwork (e.g. general for most TCIs, project change management, heater sizing, automatic planning of reinforcement, prefabricated building elements)	2	Consultant 5, 6
Benefits: 1. *Client*: No direct benefit, but more reliability of the contractor's offer, better overview, less time and cost overruns 2. *Contractor*: Transparency and control over TCI utilization to improve the construction site planning & management 3. *TCI Provider*: Precise number of items for each project to better plan the stock, focus on complex structures, where automatic calculations are not applicable, proactive role with consultancy service to address needs and requirements	12	All
Productivity and Safety: Obvious productivity increase as identified by almost all interviewees and safety improvement as a secondary effect due to more transparency, control and lean management on site	10	TCI Provider 1, Contractor 1, 3, 4 Consultant 2, 3, 4, 5, 6, 7
TCI Utilization Plan: The solution offers a tool for the automatic planning of standardized formwork elements (given some assumptions) and provides the construction site with an integrated and location-based TCI-utilization plan that can be used to better plan and manage the construction activities related to simple in-situ wall structures → Must be further tested in a pilot project to reduce the number of uncertainties and quantify the benefits	12	All

Main Findings	#	Interviewees
General Further Developments: Manual input of data, active tracking of TCIs on site with IoT-sensors and the integration of other TCI types are mentioned as general further developments	-	-
Data Integrity: Data integrity is a very important aspect in such an integrated and data-driven process and requires a QA-process to ensure that the input data complies with the specifications	5	Contractor 2, Consultant 3, 4, 5, 6
Standardization: Standardized ontologies must be established to describe the building data in its holistic context in order to ensure the success of the solution	5	Consultant 2, 3, 4, 5, 6
Centralized approach: Creating a solution-integrated and more advanced TCI engine which can calculate the precise project demand for different TCI types (based on default TCIs or real products) and derive a utilization plan	3	Contractor 1, Consultant 3, 7
Decentralized approach: Outsource the calculation engines towards the different TCI providers who act as consultants for their specific product. TCI supplier receives the required project data and calculates the TCI demand for his products based on the given project data, using an advanced calculation engine, and provides the service of planning and managing the items on the project	5	TCI Provider 1, Consultant 2, 4, 5, 6
Accessibility: Easily accessible information for people who actually use the data in their work (dashboard for the project managers and mobile application for the construction workers) and by that, solution reaches all relevant stakeholders	11	Client 1, TCI Provider 1, Contractor 1, 2, 3, Consultant 2, 3, 4, 5, 6, 7
Lean Management: The created knowledge and transparency of the TCI utilization must be integrated into site planning in order to optimize the site layout and logistics and enable a lean site management	5	Contractor 4, Consultant 2, 3, 4, 5
Contractor Business Model: As the contractor benefits the most from implementing the solution, the business model should be created for him. A contractor with a Design & Build contract has the whole value chain under him and is able to control the data flows and require certain specifications from the involved parties and thus, can easily implement such a solution	5	Contractor 1, 3, 4, Consultant 4, 6
Linked Data Vision: Linked Data project delivery vision where all stakeholders generate and own their data, but provide their product information as a consultancy service to the linked project environment where it is integrated into the data model → Decentralized nature of the project delivery will be the future when the focus will go more towards the data model and not the isolated software solutions	3	Consultant 2, 4, 5

Table 9: Main findings of the evaluation interview

6.3.2 Findings by Categories

After presenting the main findings in table format to give a quick overview, the following chapter is presenting the findings of each category in written text, allowing to also include personal statements as quotations. Quotations and other personalized statements are identified as very powerful to display information from a qualitative interview (Flyvbjerg 2004). The statements are accompanied by the number of interviewees who claimed the statement. This number is written in number format in order to increase the visibility of the quantity, it expresses. A more detailed version of the interview findings is attached as **Appendix 6.4**.

0. **Current Practice on Construction Projects**

From the perspective of all interviewed consultants and Contractor 4, TCIs are only considered in a very primitive and manual approach in which the demand might be estimated as a percentage of the total costs or with a rough and Excel-based calculation from a model-extraction. In comparison to that, Contractors 1-3 reveal that in their experience, TCIs are considered in the site planning and management. However, there is no standard and automated approach and it depends a lot on the contract, size, and type of project, in which level of detail they are considered. Furthermore, half of the interviewees claim that there is a general tendency of the site manager to order much more TCIs than needed in order to ensure a consistent construction flow and minimize the risk of resource shortages. In this context and according to Contractor 4, the main driving force of TCI planning in current practice is to ensure that the schedule can be followed, leading to over-dimensioned TCI orders to ensure that the TCI demand is met at all times. This lack of planning consequently leads to a lack of transparency that again results in items getting lost/ stolen or the construction workers simply put a lot of effort in finding the required TCIs on the construction site, as mentioned from Contractors 1 and 4 as well as Consultants 2, 3 and 4.

1. **Benefits**
    a. **General**

11 out of 12 interviewees agree on the solution's potential to bridge design and construction by using an integrated data environment and bringing BIM data to the site, where site planning and management can benefit from the improved control and transparency of the TCI utilization.

According to the interviewees, this will lead to leaner and safer management of the construction site, with less waste of time, money, resources, generally more space on site as well as improved productivity and safety. Here, the solution is not only enhancing the construction phase of the project but also allows early consideration of TCIs in the project planning as acknowledged by TCI Provider 1, Contractor 1 as well as Consultants 4 and 6. By integrating TCI-Information and supplier expertise early in the project, the construction workflow is planned in advance, improving decision making and enabling a continuous as well as efficient production with a forward-looking and lean approach. Consultants 2, 4 and 5 moreover validate the solution scope as it tries to solve a real and complex problem in the construction industry with an open-source and standard approach. According to 5 representatives of consultancies, the automatic generation of a TCI utilization plan, by using and integrating existing project data, is targeting a niche in construction which is not yet fully optimized. The use of a data-driven approach for delivering construction projects is also supported by Consultants 5 and 6 because the development of a data model has a big potential in the industry and can be applied to many different areas, not only for planning and managing TCIs.

b. Client

All interviewees agreed that the client does not benefit directly from the proposed solution, although he might experience some general improvements in projects, where the proposed solution is applied. A client benefits, for example, from a better and updated project overview and more transparent construction site, reducing risk and uncertainty, as highlighted from 9 interviewees. Still, 6 interviewees furthermore claim that a better planning with automatic TCI consideration also increases the chance of following the schedule without cost and time overruns. Furthermore, a total of 8 interviewees confirm that the client would get a more reliable offer of the contractor and fewer claims during construction as TCI-related parts are quantified with a thorough and transparent calculation, based on the tender material and not based on an untransparent and rough estimation.

c. Contractor

For all the questioned experts, the contractor benefits the most from the developed solution. In the opinion of 10 interviewees, automatic planning of TCIs adds great value in terms of transparency and control over the TCI utilization. This counts at least for simple structures in big in-situ concrete projects regarding formwork. According to 8 interviewees, the contractor could, already early in the project, assess the TCI requirements and plan as well as manage the construction site layout and logistics accordingly. During the interview, TCI Provider 1 shared one experience of a contractor claiming: "*Soon I'll be running out of space on the job site to put the formwork. Where shall I put the formwork?*" Using the developed solution, as all contractors confirm, would enable a dynamic stock consideration with just-in-time delivery and lean site/ space management that reduces the number of elements that are stored on site which is directly reducing the costs of rent of the planned items, the waste of valuable storage space on site and the effort of moving these items around. A balanced group of 8 contractors and consultants also acknowledge that the solution allows to optimize the whole production flow and to have a more efficient and lean management process of TCIs, eventually leading to a decrease in time and costs of the construction site. The proactive TCI consideration for the contractor furthermore reduces the dependency on the supplier and allows the contractor to order the precise number of TCIs from the supplier proactively and in advance based on the calculated TCI utilization plan.
A total of 5 also mention that they can automatically and in real-time, gain knowledge about which items are currently in use, what is the current stock on site as well as which items will be needed in the future. The information is always up to date as the system considers changes in the building model as well as the project schedule.

d. TCI Provider

The first impression regarding the TCI provider is that the increased transparency of the contractor for TCIs naturally interferes with the interest of the TCI provider to maximize the number of items, they deliver to the construction sites. This concern is shared by 4 interviewees. In contrast to that belief, 5 interviewees of which 2 are building contractors and 1 a TCI Provider claim that TCI provider actually benefits from better planning from the contractor side.

If the contractor knows exactly when, which TCIs are needed where on site, the provider can deliver just-in-time, minimize its own stock, closely collaborate with the construction sites and benefit from the generated knowledge about the TCI utilization from the construction projects.

e. Productivity

According to most interviewees (10 out of 12), the solution results in an obvious productivity increase due to more transparency, control, and lean management on site.

f. Safety

The second goal of the developed solution, increasing safety on site, is confirmed by 9 interviewees, although it is stated that safety is generated generally as a secondary effect of a better and more transparent planning and management of TCIs. According to 5 interviewees, safety is also positively affected if specific safety measures are applied in order to raise the awareness of and increase safety for each specific task. To name a few:

- Safety-Risk-Factor with notification
- Assembly instructions for site workers
- Checklists for each task which TCIs are installed and what is missing

2. Validation and Further Development

a. General Validation

Generally, all interviewees agree that the solution offers a tool for the automatic planning of standardized formwork elements and provides the construction site with a transparent, integrated and location-based TCI-utilization plan that can be used to better plan and manage the construction activities related to formwork utilization for simple in-situ wall structures. Although the solution already incorporates a functioning system that is able to add value to the construction site, several limitations and required improvements are identified during the evaluation interviews.

7 interviewees inform that the solution is only addressing the use case of formwork elements and therefore only benefits construction projects with a large number of in-situ walls. Furthermore, also 7 interviewees recommend that the next step of prototyping would be to apply the solution to a construction site where the process of constructing in-situ walls is analysed without the use of the proposed solution and with its utilization and where the real benefit of the solution can be quantified. This would reduce the number of uncertainties in each step of the solution implementation and include the interests of all involved stakeholders for the further development. In this context, another 6 interviewees claim that the prototype needs to be tested on site in a small pilot project to check its functionality and to get feedback from the workers who will use and benefit from it. Especially in such a conservative industry, it requires a lot of effort in terms of change management to successfully and holistically implement such a solution, as mentioned from all contractors as well as TCI Provider 1 and Consultant 4.

b. General Further Development

Generally, all interviewees recommend to further develop the proposed solution before applying it to the industry as a product or service. Contractors 3, 4 as well as Consultants 2 and 4 would like the solution to also integrate other TCI types than formwork elements. As examples for TCIs that can be included in a similar approach as formwork, the interviewees named scaffolding, safety barriers and supporting structures. Consultants 2 and 4 moreover acknowledge that an active tracking with location-sensing IoT-sensors would further strengthen the solution and the control of the site manager.

Another group of 4 interviewees also suggest introducing a more manual control of the TCI utilization plan, enabling the users to flexibly change the master plan according to the site circumstances which are not covered by the 3D-model and the schedule. Also, the collaboration aspect between the site manager and the construction workers should be enhanced.

c. Data Sources & Extraction

First of all, 3 interviewees agree that using a default TCI dataset is a good approach at the beginning of a project to get a first estimation in order to get an overview of space and logistics requirements on site and to compare bids of potential suppliers.

Yet, a few important improvements were suggested by the interviewees. The first requirement for such an automated solution is to have a data-driven project delivery with structured data. A total of 6 interviewees confirm this statement along with highlighting the scarcity of structured data in the construction industry as using data in construction is a relatively new approach to which the industry has to adapt. 7 interviewees propose to advance the solution to an open standard approach that works with multiple BIM software applications or open BIM standards and is not dependent on specific software applications as Revit or VICO. This can be achieved by either having a solution that uses standardized data sources (e.g. IFC-models) which is then parsed to RDF or the software applications can automatically extract the data as Linked Data (in RDF triples) and publish it directly to the Linked Data project environment.

Furthermore, several interviewees set the focus on the quality assurance aspect of the data sources. All consultants claim that first, there is a need to establish a standardized ontology framework in the industry to describe the building data (e.g. the building elements, the schedule information and the TCIs) in its holistic context and enable everyone to specify the data with a standardized language. 3 interviewees also identify the risk that the modelled elements are not modelled correctly which strongly affects the functionality of the TCI utilization plan. Generally, there is a risk that the data sources might not comply with the requirements to use such a solution. Thus, a quality assurance process with an automatic and rule-based data analysis is needed to ensure data integrity and the functionality of the solution. In this context, Consultant 5 mentions that Linked Data offers such an approach with SHACL (Pauwels and & Zhang 2015), a validation engine for verifying graph-based data against a set of conditions.

Finally, 7 interviewees from all interviewee groups highlight the importance of considering the technology level of the stakeholders who would interact in a data environment with this solution. Thus, again, this statement strengthens the call for enabling a manual input within the totally automatic system architecture.

d. Data Management

Using a data management approach with the open data format Linked Data was very much appreciated by Consultants 2 and 5 as it can disrupt the industry and improve collaboration. Consultant 6 added that the integration of the Linked Data approach in the existing process of BIM-based project delivery facilitates the general application of the solution in the industry. However, 4 consultants also claim that the solution could also work with usual data integration and the use of open APIs to extract the data, although the approach of generating a data model and using a Linked Data environment, especially for Consultants 2 and 5 is the way to go in order to enable open data integration in the industry that can be extended intensively (e.g. by integrating IoT-data, product data and GIS-data). Using common data integration would ease the implementation of the solution in the current industry as Linked Data might require more change and implementation efforts.

e. Data Processing & Querying

The statement, the interviewees mentioned the most in this category is the need for enabling a manual input in the automated solution as a fully automatic solution might not be able to cover the full range of complexity in the building model. A total of 8 interviewees claim that the proposed solution is perfect for automating the planning of formwork for simple wall structures, but a manual approach is needed for more complex structures as well as changes during construction which are not covered by the model or the schedule. Here, Consultant 7 acknowledges that a solution, which solves 80% of the problem but requires a lot of effort to solve the last 20% of the problem, is approaching difficulties in the implementation in real life. During the process of conducting the interviews, two different approaches have been ideated how the data processing part of the solution shall be designed.

Option 1 is supported by 4 interviewees (Contractor 1, 4, Consultant 3, 7) and recommends a holistic TCI planning tool that utilizes a solution-integrated and more advanced TCI engine which is able to calculate the precise project demand for different TCI types with all their supplementary items and derive a utilization plan. In contrast to this approach, 5 interviewees (TCI Provider 1, Consultant 2, 4, 5, 6) suggest outsourcing the calculation engines towards the different stakeholders who act as consultants for their specific speciality as they argue that one closed solution cannot do everything and it requires an open solution that integrates stakeholder expertise actively into the project development. In this second option, the TCI suppliers receive the required project data and provide the demand of their specific products with the use of an advanced calculation engine as well as the service of planning and managing the items on the project. The Linked Data environment assists this option by providing a framework for open data exchange from a centralized data model. In this context, Consultant 4 mentions a solution that was developed by TNO, a research organisation in the Netherlands, which proposes a decentralized process of planning and managing construction where intelligent online systems (BIM Bots) integrate stakeholder expertise into the project delivery and perform various tasks within the project. This solution strongly correlates to option 2 and therefore, is recaptured in the next chapter in order to discuss the answer to the main research question **RQ0**.

f. Data Visualization and Distribution

Almost all interviewees (11 of 12) inform that by visualizing the data with a dashboard for the management and a mobile app for the construction workers, the developed prototype provides easily accessible information for the people who actually benefit from the TCI utilization plan in their daily work. Contractor 3 also experienced good results with installing a big screen on the construction site for providing a weekly overview in regular meetings. This idea is also shared by Contractor 1 and 4. As a further development, 4 interviewees name data visualization in a digital 4D-site plan as beneficial as it would allow the workers to review the digital twin and also allows a safety professional to analyse the process digitally and thus, prevent accidents. In contrast, Consultant 5 claims that this would overcomplicate the 3D-model and it is better to only work with data and then visualizing the data in a tailor-made approach as with the dashboard and mobile application.

Hereby, Consultant 6 also claims that an auto-generation of shop drawings, showing how the TCIs have to be installed is sufficient and an integration back into the building model is not needed because the construction workers only need to get visually instructed how to execute the tasks. Contractor 4 and Consultant 7 also mention that using augmented reality to compare what is planned to what is installed, would be an interesting further development.

g. Active Tracking with IoT-Sensors

As already mentioned earlier, there is a strong belief that an active tracking of TCIs on site should be the next step of the solution development. A total of 7 interviewees declare that this would, even more, increase the transparency and control over the TCI management with real-time data from the construction site which is not only providing knowledge where the TCIs are supposed to be, but where they are actually located to compare planned versus reality. According to the interviewees, IoT-sensors are quite easy to implement as the solution is cheap, easy to use and can be integrated into the proposed system architecture. Moreover, an active tracking would reduce the responsibility of the workers to track their work manually which consequently reduces the risk of human failure. An alternative to IoT-sensors which actively send location information of the items, an image recognition solution could be used to recognize TCIs and their location or the items could be equipped with QR-codes which update and provide information by scanning the code.

h. Scalability of the Solution for other TCIs

Regarding the scalability of the solution, 11 interviewees claim that the open system of the solution can be applied and scaled to many different TCIs that have a relation with what is modelled and therefore can be quantified by a rule-based calculation engine. Hereby, consultants 3 and 5 inform that each TCI type would require an individual ruleset to calculate its demand for the project. This can either be done with a closed and holistic TCI calculation tool (option 1) or a generic platform to which all kind of service providers in the construction project could integrate the demand of their products for the given project specifications (option 2). Especially the further extension of the solution to integrate scaffolding and safety barriers, stated by 5 interviewees, is considered crucial to increase the safety consideration on site.

TCI Provider 1 and Consultant 6 furthermore mention that there is a big potential in applying the solution to the precast industry for planning and calculating the demand of supporting structures, especially for Denmark as there is a big market for precast elements.

i. Integration to Site Planning & Management

A further category that was developed inductively highlights the importance to integrate the developed data further into site planning and management. 5 interviewees claim that the created knowledge and transparency of the TCI utilization must be integrated into site planning in order to optimize the site layout as well as logistics and enable lean management. It is informed that the solution is only providing the raw data of how much is needed for which task where on site, but does not suggest, for example, where it has to be stored before and after use. Thus, a digital integration into a site and logistics optimization tool shall be targeted. According to Contractors 1, 3, 4 and Consultants 3, 4, the proposed prototype provides all information to generate a data-driven site and logistics plan as a location-based integration of construction elements is the key for enabling a more efficient site management. Such a site optimization tool can be enhanced by writing back the TCI utilization data to the schedule and model. This would enable to try out different scenarios of the model or schedule for improving the project delivery and with an integration of advanced technologies as Artificial Intelligence (AI), a holistic and intelligent integration of the construction process into design considerations would be possible. Lastly, Contractor 4 as well as Consultants 3 and 5 mention that an active tracking of the TCIs via IoT-sensors would further foster the integration of the solution into site management.

3. Business Model

a. Integration in Existing Project Delivery (Current Industry)

This first part of the business model category is exploring the implementation of the proposed solution in the existing project delivery and the current situation in the construction industry.

As Contractor 1 explained comprehensibly, the Linked Data approach requires a lot of effort in terms of standardization, quality assurance of the used project data and a general increase of the level of technology and an open mindset regarding new technologies of all stakeholders in the industry. Considering these limitations, 5 interviewees recommend using the solution with its proposed system architecture and some identified modifications as the industry is not yet ready for a decentralized and fully data-driven project delivery.

Here, a general contractor with a Design & Build contract could implement the solution as they would benefit the most and have the whole value chain under their responsibility, enabling to control the data flows. The contractor should also set up an ICT agreement which requires project parties (architect, engineers and sub-contractors) to establish a more open data environment and comply with the specifications in the ICT agreement in order to assure full functionality of the proposed solution. However, this business model requires the contractors to be involved early in the project as otherwise, it is difficult to demand certain data integrity from all project parties. According to other 5 interviewees, a consultant could be involved for implementing the solution, who is introducing the solution in a pilot project, from which onwards, the contractor will gradually get familiar with the solution and incorporate it in their processes. This is also supported by TCI Provider 1 as well as Consultants 2 and 3 who acknowledge that only providing a software solution is not sufficient, as there is always a need to accompany the software with a consultancy service.

The solution for this business model can either be set up with the Linked Data environment or with open APIs of the different software applications with usual data integration. However, both approaches require an intensive effort of standardization to ensure the solution's functionality across the construction industry.

b. New Project Delivery System (Linked Data Vision)

Besides the integration of the proposed solution in the existing project delivery, the interview findings envision a future project delivery system as the Linked Data approach introduces a way to unlock a huge potential for the construction industry.

Consultants 2, 4 and 5 propose a Linked Data project delivery vision where all stakeholders generate and own their individual data but provide it to the linked project environment where it is integrated into a central data model. According to them, the decentralized nature of the project delivery will be the future when the focus will go more towards the data model and less towards the different software solutions. In this approach, the different stakeholders would provide their information as a consultancy-as-a-service for a specific part of the project. Here, 4 interviewees highlight that new roles and responsibilities will arise in the market and the industry must go in this direction of getting better data. In the Linked Data vision, one party is centrally hosting the data model from the beginning of the project and integrates as well as shares the data from and with the different parties involved in the project as the project evolves. According to Consultant 5, a suitable development would be to make the BIM authoring tools automatically extract the data as Linked Data (in RDF triples) to directly communicate with the triple store of the data model. With the new project delivery system and a centralized data model, the contractor would gain most access to the model during the construction phase in order to plan the construction site and logistics and have more control over the construction flow. Supplier and sub-contractor would only gain access to the specific data, they need to calculate the demand for their product/ service. Subsequently, they would integrate the project-and task-specific output into the data model to add value to the project. At least Contractor 3, as well as Consultants 2, 4, 5 and 6 think that this scenario is realistic in future as the industry is aiming towards a more data-driven approach. However, they also mention the requirements for a change in the mindset of the people to work in an open project environment and for a standardization process in the whole industry to develop the required ontologies.

With the presentation of the interview findings in the categorized order, it is possible to answer the last sub-research question. **RQ4** asked whether the added value of the proposed solution can be verified to ensure its success. This question was approached by conducting evaluation interviews with 12 different experts in the construction industry. Thus, the input, given by this diverse and knowledgeable group of experts is considered valid to answer the fourth research question.

Generally, almost all interviewees would appreciate such a solution in the construction industry and confirm the potential of automatically deriving a TCI utilization plan from the existing BIM-based project data in order to better plan and manage temporary construction items on a construction site, hence verifying the added value of the proposed solution for the industry. As the interview findings comprise not only the validation but also recommends further developments for the prototype solution, also the second part of **RQ4** is approved. By reflecting upon the limitations and further improvements with the expert knowledge from different industry stakeholders, the future success of the solution is ensured, given the fact that the process of prototyping is continued and follows the developed recommendations.

As all of the developed sub-research questions are now answered, the next chapter is starting a discussion to finally answer the main research question of this thesis project aiming at developing a more lean and integrated planning and management process of temporary construction items.

Chapter 7: Discussion

The prior chapters have provided answers to the four raised sub-questions, which will be reflected upon and combined in the subsequent discussion in order to answer the main research question of this paper: *"How can productivity and safety issues at construction sites be resolved by improving the site and logistics management of temporary construction items?"*

By discussing and summarizing the research findings, this chapter furthermore aims at deriving a process integration of the developed prototype solution, presenting the different project phases in which the solution can be applied and revealing the benefits for each phase. While this process integration gives a general overview of the functionality of the solution, the successive chapters explore two different scenarios on how to implement the solution in the construction industry. On the one hand, the current industry situation with the existing project delivery is taken as the underlying foundation to implement the proposed solution and on the other hand, a new project delivery approach is outlined, comprising a future vision for the construction industry.

7.1 Recapturing Findings from Research Sub-Questions RQ1-4

This section of the discussion revisits all answered sub-research questions to discuss how they were addressed previously. The research sub-questions, derived in chapter 4.2 and investigated in chapter 5 and chapter 6, are:

RQ1: *How are temporary construction items planned and managed in projects?*

RQ2: *How can this process be improved in a simple way?*

RQ3: *How to integrate TCI data to the existing BIM process and with that, create value for the project?*

RQ4: *Can the added value of the proposed solution be verified to ensure its success?*

Coming back to the first sub-question, which aimed at investigating how TCIs are currently planned and managed in construction projects, formwork was selected as a TCI representative for this thesis. The context of formwork operation in the current industry was first explored with findings from literature, expert interviews and site observation. As a result of the chapter and main input for **RQ1**, a flow chart of current practice in estimating, controlling and managing items on site is derived from Kim and Teizer (2014) and adjusted to the context of formwork.

It is identified that considering TCIs in construction is a reactive process where only little effort is used for planning, resulting in a huge effort for managing the items later on site.

Thus, the second research question intends to address this issue by exploring how this process can be improved in a simple way. The answer is by automatically planning the formwork demand and integrating the information into the existing BIM data to derive a TCI utilization plan that provides the construction site with transparency and control over the regarded items. Following up on the high-level framework of an innovative management process for TCIs (cf. Figure 11), from chapter 3, by answering **RQ2**, the author developed a detailed process map for integrating TCIs in a BIM-based project layout and enabling an automatic planning and lean management (cf. Figure 21). What is more, the input to **RQ2** also gives an introduction to the Linked Data environment, which is utilized in the solution development to manage the data and further presents a vision of a more integrated and data-driven project delivery in the industry.

After conceptualizing the solution layout, **RQ3** then addressed the implementation of the concept into practice, calling for the development of a functioning prototype solution. Answering the third sub-question, value creation with the integration of formwork data to the existing BIM process is achieved by letting a calculation engine first calculate the formwork demand for each building element and by subsequently deriving a TCI utilization plan with the further integration of LBS-data. Visualizing the data as a final step of the prototype development is generating customized value, specifically for the stakeholders who are in need of the information. Concluding the task of answering **RQ3**, a fully functional prototype for automatically planning the formwork utilization for a construction project is developed and validated in a case study.

RQ4 comprises an extended consideration of managing innovation by introducing the evaluation aspect to the theory. Evaluating innovations in the construction industry was identified to be important and thus, a group of highly experienced and skilled experts validated the developed prototype and derived limitations asl well as further improvements. By reflecting upon the proposed solution, the author takes into account the current status quo of the prototype development and thus, presents a well-balanced and reflected solution for answering the main research question but also leading the discussion towards the framing of a future vision as well as an objective conclusion to inform about the limitations as well as required further development of the prototype.

7.2 Lean and Integrated Process of Planning and Managing TCIs (Answering RQ0)

Based on the current state of the developed prototype and the answers to all sub-questions, this chapter revisits and subsequently answers the main research question by deriving a process integration of the proposed solution in the current project delivery practice of construction projects, determining whether the solution is able to improve productivity and safety issues on site. The overall research question, aiming at achieving the defined **research objective** to develop an integrated and lean management process of temporary construction items with an integrated and data-driven information flow between planning and construction to improve productivity and safety on site, is recaptured below:

RQ0: *How can productivity and safety issues at construction sites be resolved by improving the site and logistics management of temporary construction items?*

In reference to the qualitative findings in the evaluation interviews, most of the experts confirm that the proposed solution, besides others, provides the benefit of improving productivity as well as safety on a construction site. Hence, it is considered a valid conclusion that the developed prototype solution provides an answer to the main research question and furthermore, approves the **hypothesis** that existing technologies and methods have the potential to overcome the challenges regarding construction logistics management of TCIs in the construction industry, and hence improve productivity and safety on site. In order to address specifically, how the developed solution is implemented in the project delivery process, a process integration must be generated, identifying the created value from the solution utilization in each project phase. During the interviews, a few experts, above all Contractor 2, furthermore addressed the need to visualize how the solution might be integrated into the existing project delivery process and how the stakeholders benefit from the implementation. Based on this recommendation, the following process is generated. By taking into account all the previous findings and providing an answer to the main research question **RQ0**, the process gives an overview to better grasp the scope of the solution and its utilization in a construction project.

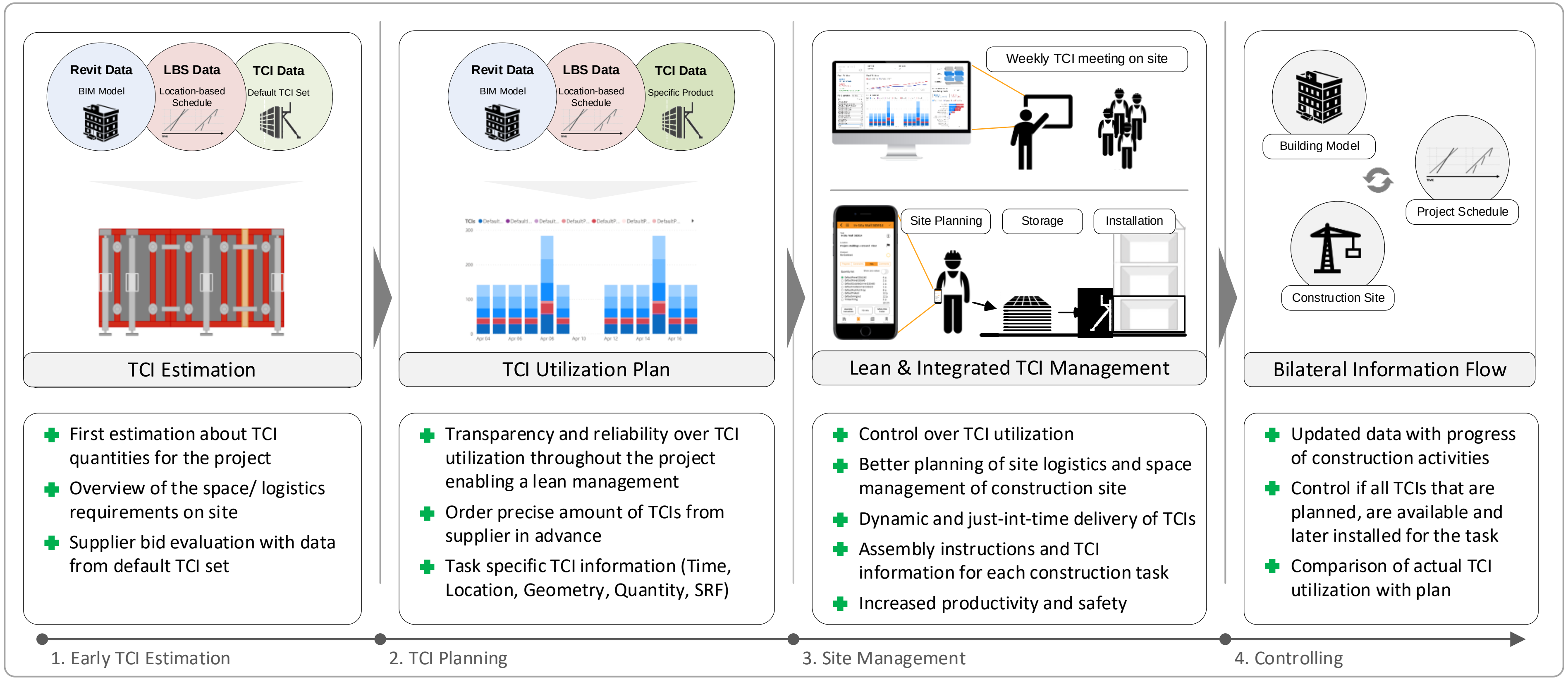


Figure 38: Process integration of the proposed solution with benefits (own visualization)

The proposed process integration in figure 38 is divided into three different steps, representing different tasks in a construction project, where the developed solution can be applied to create value. The first step takes place in the early project development, where a contractor could, based on a default TCI set, already calculate a first estimation of the TCI quantities for the project. Although, this step does not refer to real product information, calculating the TCI demand with a standardized set of default elements provides an important overview of space and logistics requirements early in a project, enabling to better plan the construction site layout and workflow. Furthermore, already having a reference to the TCI demand allows to later evaluate incoming offers from TCI providers by comparing it to the quantities of the default TCI estimation.

As soon as a specific TCI provider is selected in a project, the default TCI set can be replaced by specific product information in order to automatically create a TCI utilization plan that mirrors exactly the utilization of the items on the construction site. This is done in the second step of the process integration, called *TCI planning,* in which task-specific TCI information about time, location, geometry, quantity and safety risk is generated to add value to construction. The main benefit in this step is the transparency and reliability it provides regarding the TCI utilization throughout the project. Moreover, the transparency enables the contractor can order the precise number of TCIs from the supplier in advance to ensure an efficient production flow.

While the first two steps mainly concern the planning part, the third step, *Site Management*, reveals the potential of using the solution directly on site, realizing benefits for the relevant stakeholders. By providing two options for the visualization, the solution addresses all needs of the people who are benefitting from the TCI utilization plan. The management level of the site contractor can review the dashboard to get an overview and gain control over the TCI utilization on site over time and by location. As experienced also by Contractor 3 in the interviews, establishing a big screen in a site container, where the dashboard is displayed, is further acknowledged to be a good idea for distributing the information on site. Hence, the management level could arrange a weekly TCI meeting with the foremen, where they get instructed over the TCI utilization. Consequently, when executing the planned tasks, the construction workers can retrieve the task-specific TCI information with the mobile application. Besides a checklist, which quantities of TCIs have to be installed for the specific construction activity, the mobile application can further display assembly instruction from the supplier, how to safely and accurately install, use and dismantle the items.

Figure 39 presents both tools for visualizing and distributing the generated data to add value to the construction project.

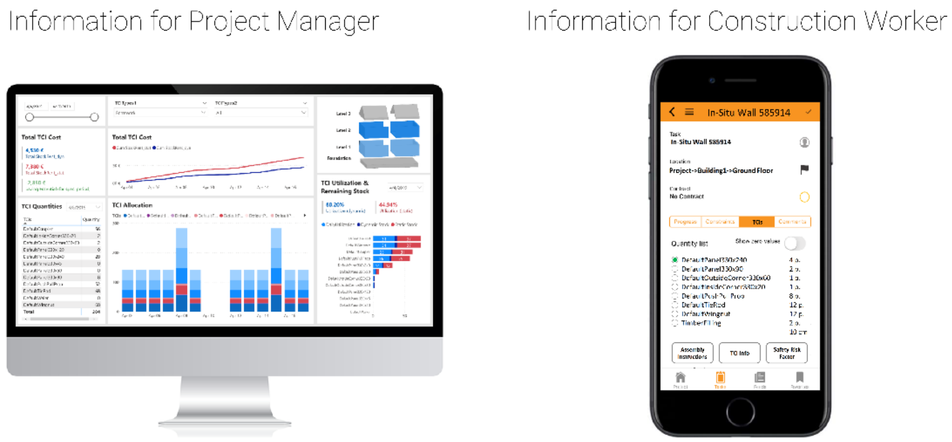


Figure 39: Tools for data distribution to relevant stakeholders (own visualization)

Applying the developed solution on site adds value to construction as it provides transparency and control over the TCI utilization. This, further leads to a better planning of the site logistics and space management, increasing the efficiency of the construction workflows. By enhancing the collaboration with the TCI provider and sharing the precise number of TCI demand on site, a dynamic stock consideration with just-in-time delivery of TCIs is enabled. This will not only reduce the amount of rent, as fewer items are stored on site but first and foremost reduces the waste of valuable storage area on site and enables lean management of TCIs which also reduces the amount of inefficient storage and logistics activities. By also addressing the safety aspect with adding assembly instructions as well as the safety risk factor for each construction task and generally providing transparency of which items are when where, the solution is able to increase both productivity and safety on a construction site.

Finally, the fourth step of the proposed process integration, *Controlling*, is generating benefits from the interlinked system architecture of the proposed solution. The solution enables bilateral information flow between planning and construction. On the one hand, changes in the building model or the location-based schedule are directly affecting and updating the TCI utilization plan. On the other hand, changes on site as delays or other not foreseen circumstances can directly be integrated into the data model by putting in the information into the progress function of the Exicute application. Hence, the provided data of the solution is always up to date according to changes in design as well as the progress of the construction activities.

Providing knowledge of all TCIs that are planned for the task, the site manager can perform a comparison of the actual TCI utilization with the plan as the construction workers would document the use of TCIs for each activity.

Having established and explained the process integration for the developed prototype, **RQ0** is not only discussed and answered in this chapter, but a utilization scenario for the proposed solution was derived from all prior findings. Resulting in outlining an integrated and lean management process of TCIs with an integrated and data-driven information flow between planning and construction to improve productivity and safety on site, the proposed process integration finally accomplishes the **research objective**, developed in chapter 3.

Completing the discussion of this paper, the following two chapters will explore two different implementation scenarios with a revised process map of the solution in order to provide a clear picture of how the prototype can be further developed and used within the current industry, but also in the future as digitalization, collaboration and standardization gain further acceptance and implementation in the construction industry.

7.3 Integration in Existing Project Delivery (Current Industry)

The first explored scenario is based on the implementation of the solution in the existing project delivery and draws upon the findings regarding a potential business model. Here, a revised version of the process map is proposed with findings from the solution development. As this also resembles the situation in which the prototype has been developed, the framework of the process map stays more or less the same as in figure 21 and is only adjusted with a few suggestions from the interviews. The following extensions are considered in the revised process map.

- IoT-technology for an active tracking of TCIs (**Category 2g**)
- Integration of multiple TCI types as scaffolding or supporting structures (**Category 2h**)
- Utilization of the data for a better construction site planning & management (**Category 2i**)

Based on these considerations, the following process map (Figure 40) is derived, providing a revised framework of the solution for the implementation in the current construction industry.

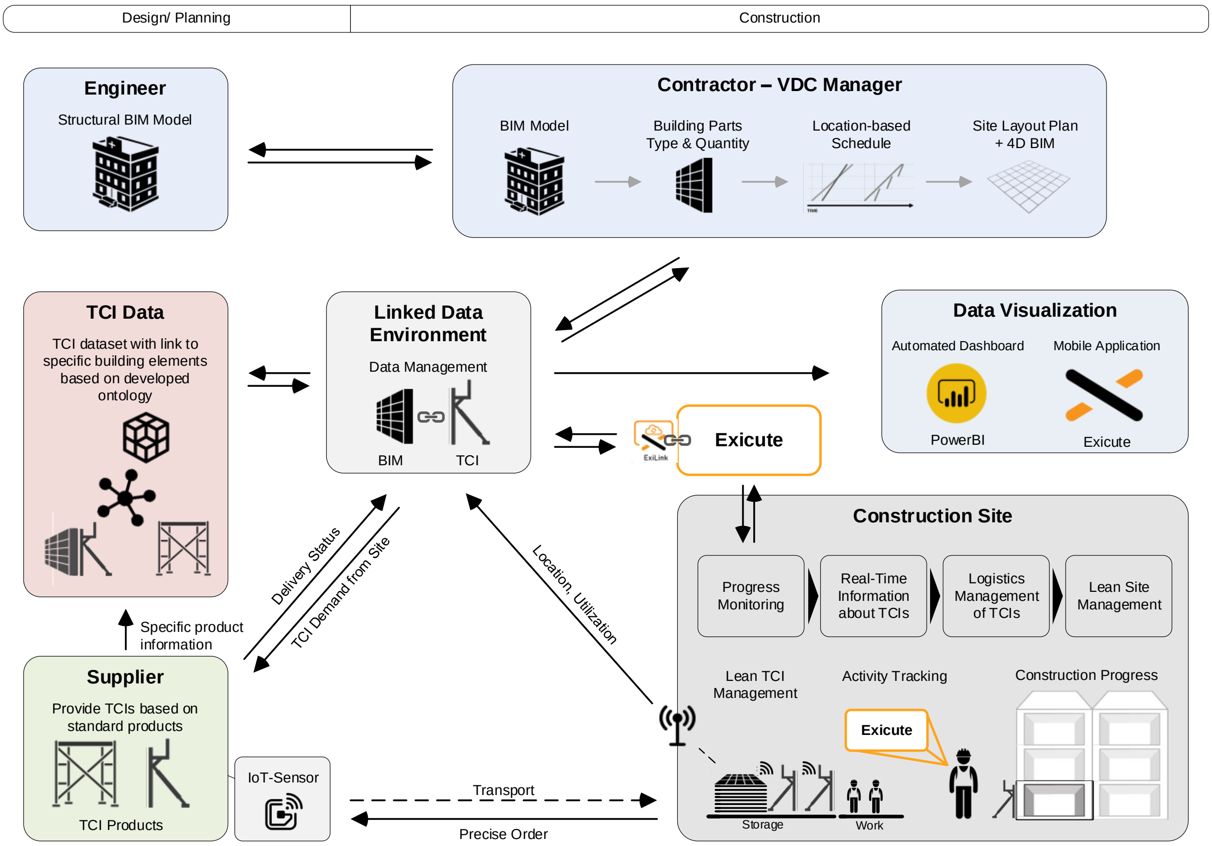


Figure 40: Framework for the implementation in the current industry (own visualization)

Reflecting on the derived framework in figure 38, it is identified that all five recommendations of the solution space deduced from current literature in chapter 2 and defined in chapter 3, to improve productivity and safety in construction by considering TCIs in planning and management, are incorporated in the developed framework. Revisiting the literature findings from the state of art report, the following listing recaptures the derived recommendations:

1) Adoption of BIM and TCIs consideration in construction for site management
2) IoT-technology for tracking construction resources
3) Cloud-based platform for bilateral information flow between planning & construction
4) Tailored dashboard visualization of monitoring information using KPI's
5) Stakeholder integration in information system

Thus, by covering all recommendations to improve productivity and safety on site, the solution is validated both by literature as well as by qualitative expert interviews and provides a potential tool to enhance current construction management with the consideration of TCIs.

7.4 New Project Delivery System (Linked Data Vision)

Suggested by several experts, the second scenario for implementing the proposed solution aims at exploring a future vision of how the developed solution can disrupt the construction industry by introducing the Linked Data approach to develop a new project delivery system.

The state of art report characterized the current industry as highly fragmented (Farmer and Branson 2016) and although the projects and construction sites become more and more complex (Barbosa et al. 2017), the conservative industry is lacking disruptive developments for decades, leaving behind a highly underdeveloped and underperforming construction industry (World Economic Forum 2016). In this context, Consultants 2, 4 as well as 5, envision a new project delivery system with an open project environment, aiming at becoming the needed disruptive change for the industry. This system would be based on a data-driven approach, where data is generated decentralised by the different stakeholders and in order to develop a rich and central data model, which is used to derive and calculate new data and further develop the construction project. According to Consultant 5, Linked Data provides the technological capabilities to put such a vision into practice, leveraging the whole industry to become a more integrated and well-functioning ecosystem. A similar vision was already outlined by Rasmussen (2018), calling it *"the vision of a decentralized, distributed AEC information infrastructure using Linked Building Data technologies"* (Rasmussen 2018, p. 1). Here, the vision aims to create a "*semantically-rich integrated*" (Rasmussen 2018, p. 1) model to which data from different disciplines can be integrated, allowing, for example, to perform engineering tasks for the project by simply applying standard equations on the data model to produce an output. With that, design and engineering work is first approached in a decentralized manner and then combined centrally to create value for the project. So far, which is also exemplified by the prior example, Linked Building Data has mainly found implementation for the design phase of construction. As described by Pauwels et al. (2018), linking decentralized data from different disciplines to a central model by using Linked Data allows to maintain the discipline-oriented characteristic of design work and simultaneously enables to overcome interoperability issues and foster an integrated design development. However, Pauwels et al. (2018) further acknowledge that having a wide stakeholder range, generating specialized information in a construction project occurs not only in design but also in "*[…] planning, construction and maintenance of the built environment*" (Pauwels et al. 2018, p. 181).

Thus, this situation is affecting the whole life cycle of a building and requires close collaboration between the stakeholders and standardized data integration from the heterogeneous domains and formats. Therefore, this chapter aims at deriving a new project delivery system, aligned to the Linked Data vision, by applying the capabilities of Linked Data and the findings of this research to the construction phase of building projects. Thus, the goal of the chapter is to propose a newly developed framework, providing a construction-specific adoption of existing Linked Building Data to unlock its potential for the construction industry.

In reference to the interview findings in **category 3b** as well as the Linked Data vision, the framework comprises a decentralized project delivery where all stakeholders generate and own their data, but provide specific data as a consultancy service in the linked project environment where the individual datasets are integrated into a central data model. From there, the enriched data model allows to distribute specific data to authorized stakeholders in order to further develop the project and derive new data. The envisioned framework can be utilized to outsource the calculation engine of the TCI quantification towards the specialised supplier who will provide their product-specific algorithms to derive and link the TCI demand to the BIM data. Since this solution only integrates the results to the data model, it incorporates a potential beyond the application of TCI planning and management. Thus, all discipline-oriented tasks in a project can be managed decentralised and the results are later integrated into the data model.

As already addressed in **category 2e** of the interview findings, a research organisation in the Netherlands proposes such a decentralized system where intelligent online systems (BIM Bots) integrate stakeholder expertise into the project delivery and perform various tasks like calculations, simulations or analyses for the project, resulting in fewer design and construction errors. BIM Bots are smart tools, retrieving data directly from the BIM environment, automating the communication and information transfer between the involved stakeholders as well as early integrating their expertise to generate "*time gains, cost savings and greater efficiency*" (TNO 2020).

While the following framework in figure 41 outlines the decentralized project delivery system for the application of TCI planning and management, utilizing a TCI calculation engine that is provided by the TCI provider, it is identified that the vision of a Linked Data-enabled and distributed information infrastructure for the construction industry can be applied to various tasks in the lifecycle of the built environment (Pauwels et al. 2018; Rasmussen 2018).

In contrast to the framework of the previous chapter, this framework describes a future vision of the solution and thus, contributes to the knowledge base as a recommendation for future research, proposing a scenario to overcome current challenges in the industry.

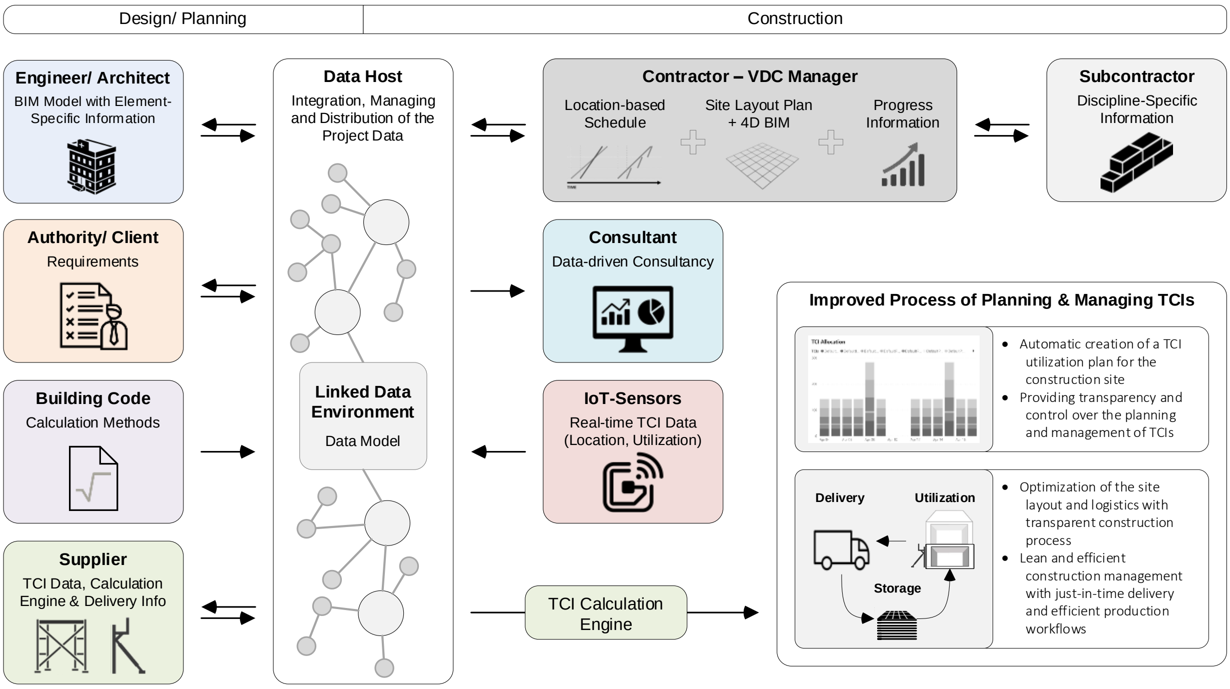


Figure 41: New framework with a new project delivery system (own visualization)

In conclusion, the new framework reveals the potential of using Linked Data for both design and construction as well as forging the link to the proposed solution. By that, a new project delivery system is proposed. Among others, four values are mentioned in figure 41, which are added to the construction site by utilizing the proposed framework for planning and managing TCIs.

Wrapping up, both developed frameworks in chapter 7.3 and 7.4 propose a process map for improving construction with a data-driven and integrated project delivery. The first scenario covers the project delivery in the current industry, whereas the second scenario envisions a new system of a more integrated and decentralized project delivery using Linked Data. In both solutions, the developed prototype can be applied to improve the management of TCIs on a construction site. Considering the identified recommendations for the further development of the prototype, its full potential can be unlocked. Based on the evaluation of several experts in the industry, the solution can then be applied as a powerful tool to improve planning and management efforts for TCIs in the construction industry.

Chapter 8: Conclusion

This paper has set out to answer the following overall research question: "*How can productivity and safety issues at construction sites be resolved by improving the site and logistics management of temporary construction items?*" In order to best answer this question, the author developed four sub-questions, that are aligned to the overall research methodology and provide the paper with a red thread from the early innovation ideation until the evaluation of the developed prototype. First, a state of art report explored the problem and solution space in the construction industry from both a theoretical and practical perspective. After framing the research to the specific challenge of planning and managing temporary construction items, which was identified to cause productivity and safety issues, a total of five recommendations were derived as potential solutions to overcome this challenge. By creating a high-level framework in consideration of the recommendations, the paper accomplished the first step of the methodology, searching for innovation opportunities. Selecting an innovative idea was the subsequent step of the methodology. Here, the author chose a combination of literature, interviews, and observation as information sources to develop a concept solution that allows considering TCIs within a BIM-based project in a simple way. By introducing the Linked Data environment - the cornerstone of the solution - the initial framework was further developed, comprising now the whole conceptual range of the solution. Going further, the paper put the theoretical concept into practice by building a prototype solution in two successive steps. In a demo project, the prototype was first created and subsequently further improved in a case study. While the two-folded prototype development covered the third and fourth step of *Managing Innovation* (Tidd and Bessant 2012), addressing the implementation and capture of an innovation, the paper moreover identified the need for a further method for evaluating the developed solution. Thus, as the last part of the solution development, expert interviews were conducted to validate the solution and give recommendations for the further development. Concluding the **research objective**, the comprehensive evaluation of the proposed solution leads to a discussion in which research findings are recaptured to answer the overall research question. As a result, the answer led to a process integration and the deduction of the solution's benefits for the construction industry in different project phases.

By finally proposing two different frameworks to which the developed solution can be applied, the author distinguishes between an ideal current scenario and an ideal future scenario. In the ideal current scenario, an innovation, like the developed prototype, requires the data to be extracted from the different BIM authoring tools or stakeholders and to be converted into RDF triples. The ideal future scenario, in contrast, foresees a decentral project delivery where the different stakeholders act as a service provider and integrate their specialized data into a central model, from which other stakeholders can retrieve, process, and add new data to further develop the project.

By consequently following the research methodology, this paper addressed the issue of poorly planning and managing TCIs in construction, being a risk factor regarding safety and productivity at construction sites. Thus, the developed solution is fulfilling the **research objective** as it comprises a tool for the automatic planning of TCIs that integrates existing project data into a powerful and linked data environment. The possibility to automatically plan TCIs, consequently, fosters a lean and integrated management process of TCIs at the construction site, improving site productivity and safety. Utilizing a data-driven approach with a generic perspective on a narrow problem, the solution has great potential to be further developed and applied to various areas in construction, thus, increasing its added value to the industry. Summarizing the contribution of the developed solution, its limitations as well as exploring further research, the following sections subsequently provide insights on the implications, the construction industry and academic research must draw from this paper.

8.1 Contribution

The purpose of this chapter is to identify the contributions of the research to the knowledge base. As the paper developed a specific solution for integrating TCI consideration into a construction project as well as envisions a decentralized and linked project environment, the paper contributes to both current BIM research as well as a future vision of how the construction industry delivers projects. The main contribution to BIM research is the detailed development of a tool for automatically planning the location-based TCI utilization from existing BIM data and distributing the data with customized visualization tools to enhance construction site productivity and safety.

Additionally, the data-driven approach of using information from different BIM authoring tools to derive new value for a project and illustrating it in a system architecture as well as in a framework is contributing to research efforts within BIM. Eventually, BIM research further gains value from the comprehensive solution evaluation of highly experienced experts in the industry. As Consultant 5 already analysed, the thesis holds a very generic perspective by utilizing data modelling in construction projects with Linked Data and applies it on a very narrow problem. Hence, the paper is also contributing to the knowledge base with the vision of a disrupted and better construction industry, inviting other researchers to further contribute to the same vision and practitioners to consider and eventually implement the vision.

8.2 Limitations

Limitations of this research study can be related to the paper's conceptual solution, developed prototype as well as research design. The conceptual solution is limited by the findings of the state of art review and the concept development. Analysing alternative papers, interviewing different experts or also visiting a different construction site for observation might have led to a different solution.

Furthermore, the prototype is developed based on the application of formwork. Although it is identified by the evaluation interviews that the prototype is theoretically applicable to different TCI types, the research paper lacks a proof of concept. Regarding the practical implementation of the prototype, a few assumptions and simplifications (cf. **Appendix 4**) were defined in order to keep the prototype development simple. Among others, the building model has to be designed according to the practice of the construction site, meaning that walls must be modelled as they are constructed, and the model must contain all required element properties. Further limitations of the prototype can be found in the case study documentation (cf. **Appendix 4**).

In the context of the research design, a qualitative approach for evaluating the developed prototype was chosen. Hence, the results cannot be seen as representative for the whole construction industry.

8.3 Future Research

As the developed prototype is primarily a proof of concept for the proposed solution, an exhaustive list of future research opportunities can be implied. First considerations in this direction were already made when reflecting on the case study as well as the findings of the evaluation interviews. However, generally speaking, future research must continue the further development of the prototype according to the presented findings and eventually implement the solution in a pilot project to validate its functionality and quantify its real benefit for the different stakeholders.

Although the solution framework in chapter 7.3 considers the aspect of utilizing the solution for a better site planning and management, this consideration has not yet been fully explored. In this research study, the possibility to optimize construction processes with the prototype solution is mainly addressed theoretically as a result of the developed TCI utilization plan and the created transparency. Hence, as a further research aspect, it is recommended to integrate the data of the solution into a construction site optimization tool like the Smart Construction Planner® (Guerriero et al. 2017) to improve site logistics and increase the efficiency of the construction workflows. Lastly, the author urges other researchers to contribute to the efforts of the Linked Building Data community group to further develop standardized ontologies for various applications in construction, eventually disrupting the industry to become more integrated and efficient.

Chapter 9: Bibliography

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Appendices

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Appendix 1
Scope of the Thesis

Appendix 2

Photo Documentation

Appendix 3

Demo Project Documentation

Appendix 4

Case Study Documentation

Appendix 5.1

Interview Guide for State-of-Art Report

Appendix 5.2

Interview Guide for Concept Development

Appendix 5.3

Interview Guide for Evaluation Interviews

Appendix 5.4

Interviewee Introduction

Appendix 5.5

Solution Presentation for Evaluation Interviews

Appendix 6.1

Answers of Interviews for State-of-Art Report

Appendix 6.2

Answers of Interviews for Concept Development

Appendix 6.3

Answers of Evaluation Interviews

Appendix 6.4

Findings of the Evaluation Interviews per Category

Appendix 7.1

PERI-Quicksolve_SingleWall

Appendix 7.2

PERI-Quicksolve_DemoGF

Appendix 8

GitHub Repository

The GitHub repository publicly provides access to all programs and other files that were developed and utilized for both the demo project and the case study. Furthermore, it contains the newly created ontologies as well as the submitted thesis paper, including all appendices.

The repository can be found at *https://github.com/Alex-Schlachter27/LBD-for-TCI/tree/master* and comprises the following structure.

Directory	Content
Ontologies	This folder contains the Linked Data ontologies that were created for this thesis. The main contribution is the TCI ontology, describing the whole context of TCI utilization in construction with the focus on formwork elements. The LBS ontology holds information to describe the location-based schedule. For the Revit data, no additional ontology was created as existing ones were utilized to cover the scope of describing the building elements.
Demo Project	This folder is structured in accordance with the big data value chain, providing access to the utilized files in the demo project. Going from data extraction to data visualization, it comprises all steps of the developed solution with the utilized programs, at the status of the first prototyping phase.
Case Study	This directory is structured the same way as the Demo Project folder and contains the files that were utilized in the case study application. It also contains the developed Power BI dashboard as the final result of the prototype process. As the VICO-files Take-Off-System and Cost-Plan are too large for this repository, they are submitted via the following link, containing the entire thesis submission: https://1drv.ms/u/s!AiRxOYo_ECttgYFAH3nzxFqZ-yunfw?e=EGpGxp
Thesis Submission	This folder contains the thesis paper and all appendices as separate files.