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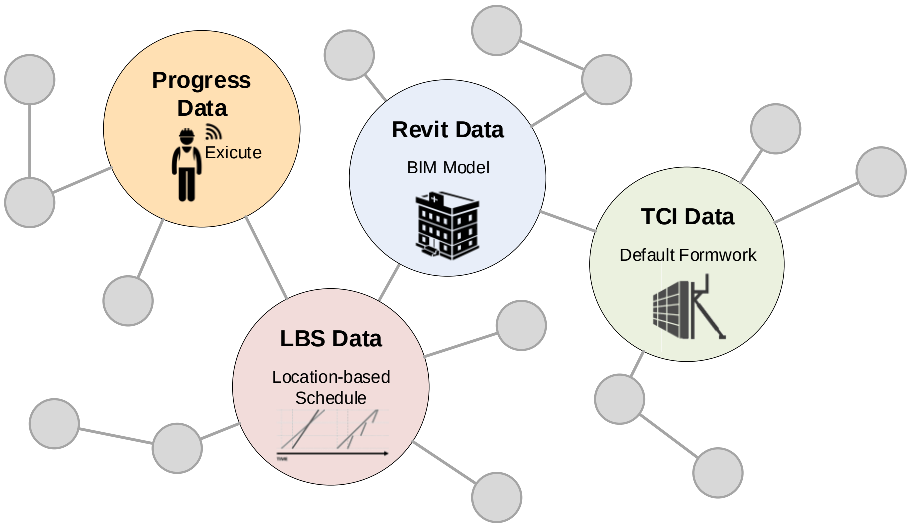

Unlocking the value of Linked Building Data (LBD)
A lean and integrated management process of temporary construction items (TCIs)

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.

Acknowledgement

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Table of Contents

List of Figures

List of Tables

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.

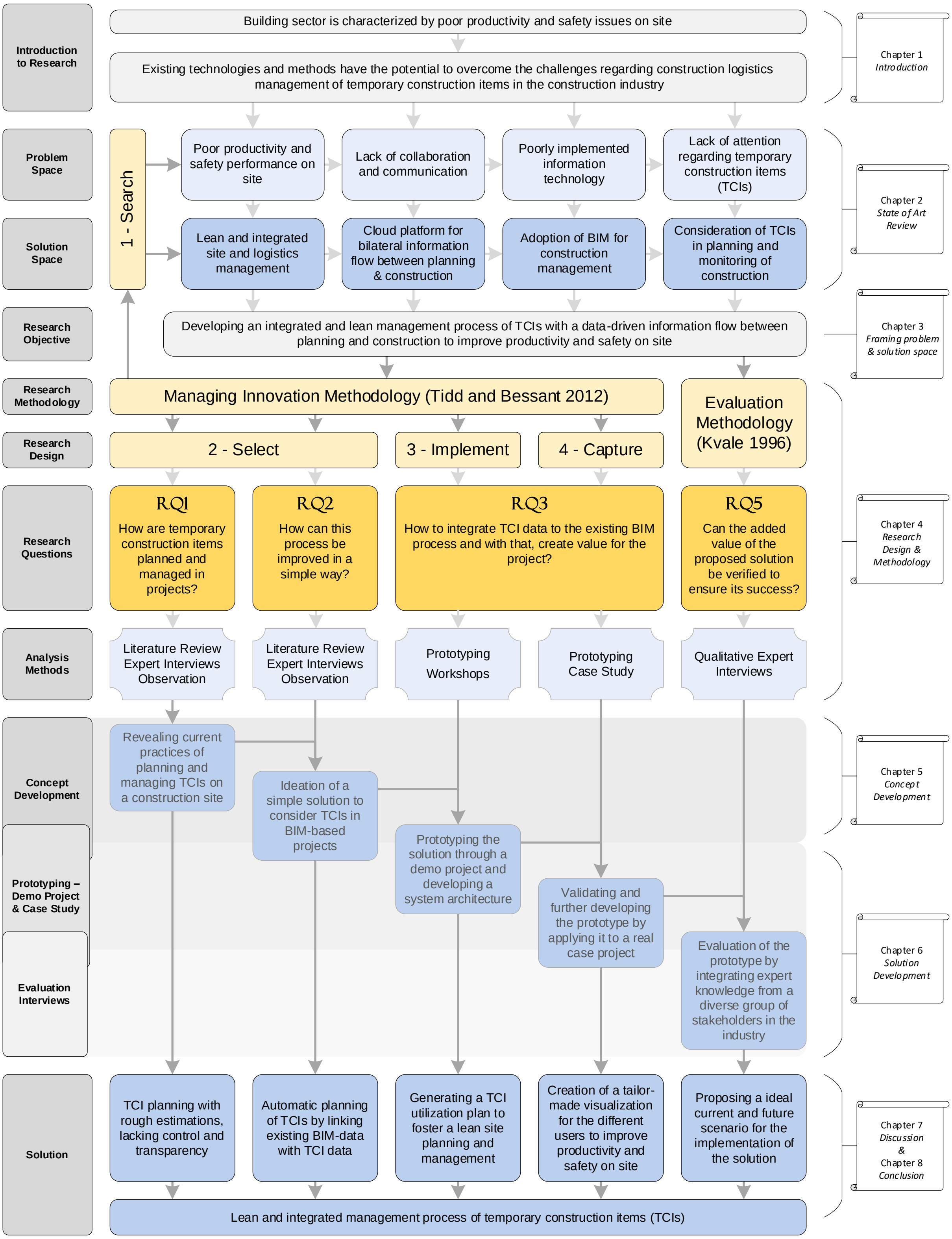

Figure 1: Structure of the research paper (own visualization)

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)

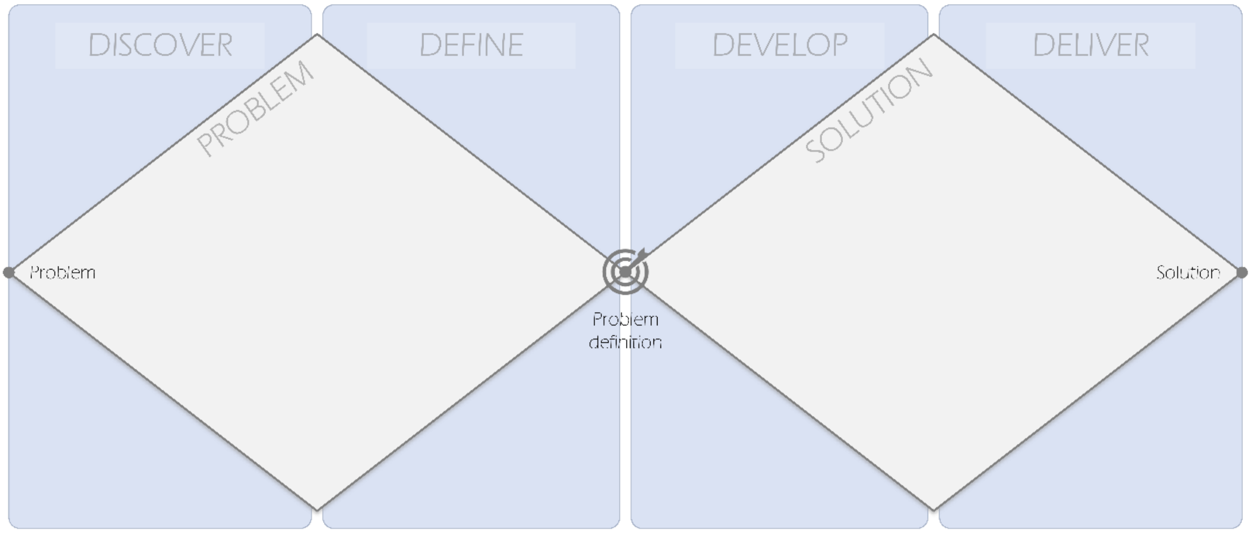

Figure 2: Double Diamond Methodology (own visualization)

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.

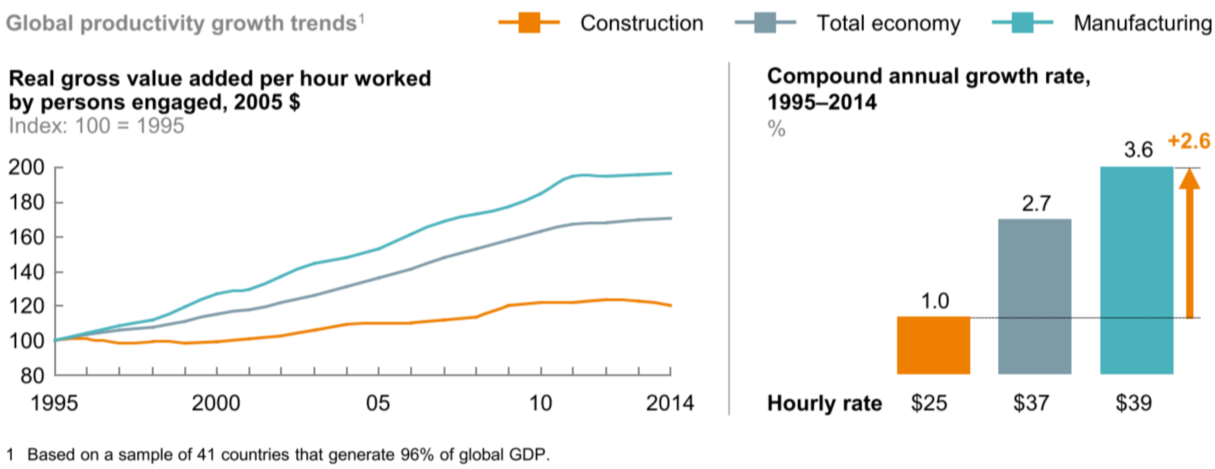

Figure 3: Global productivity growth (Barbosa et al. 2017, p. 12)

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).

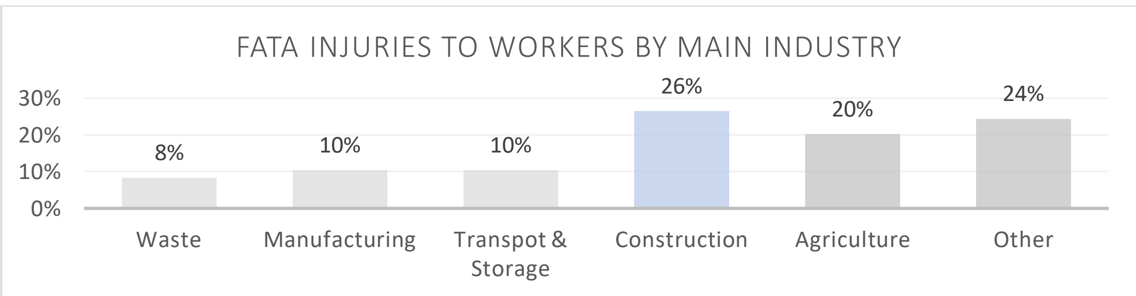

Figure 4: Fatal injuries to workers by the main industry (own visualization)

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.

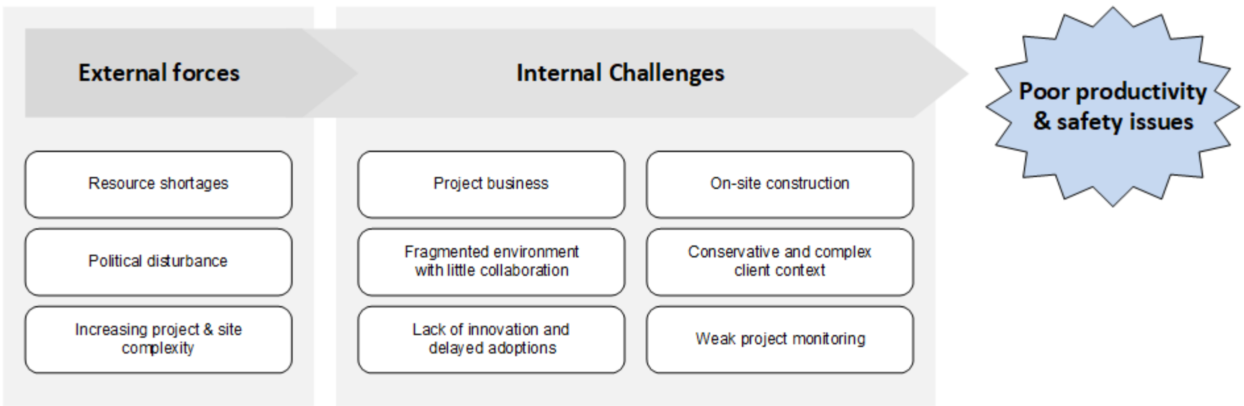

Figure 5: Root causes for productivity and safety issues in construction (own visualization)

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.

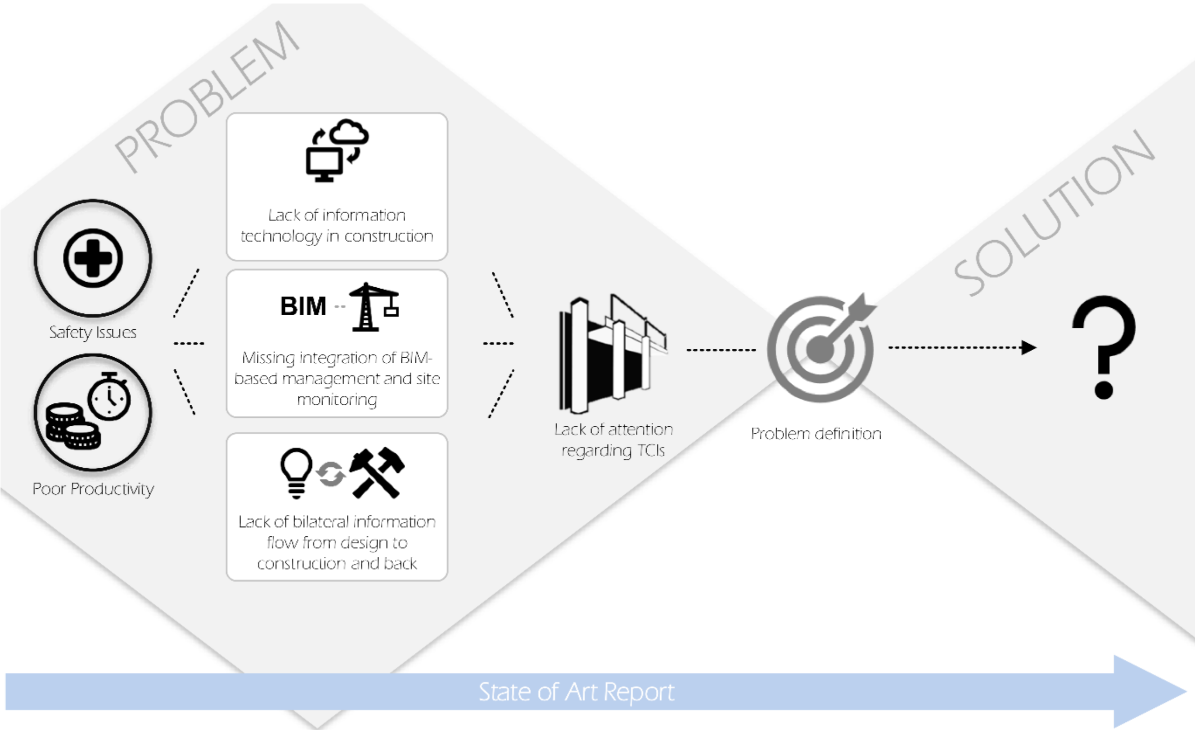

Figure 6: Summary of identified problem space (own visualization)

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).

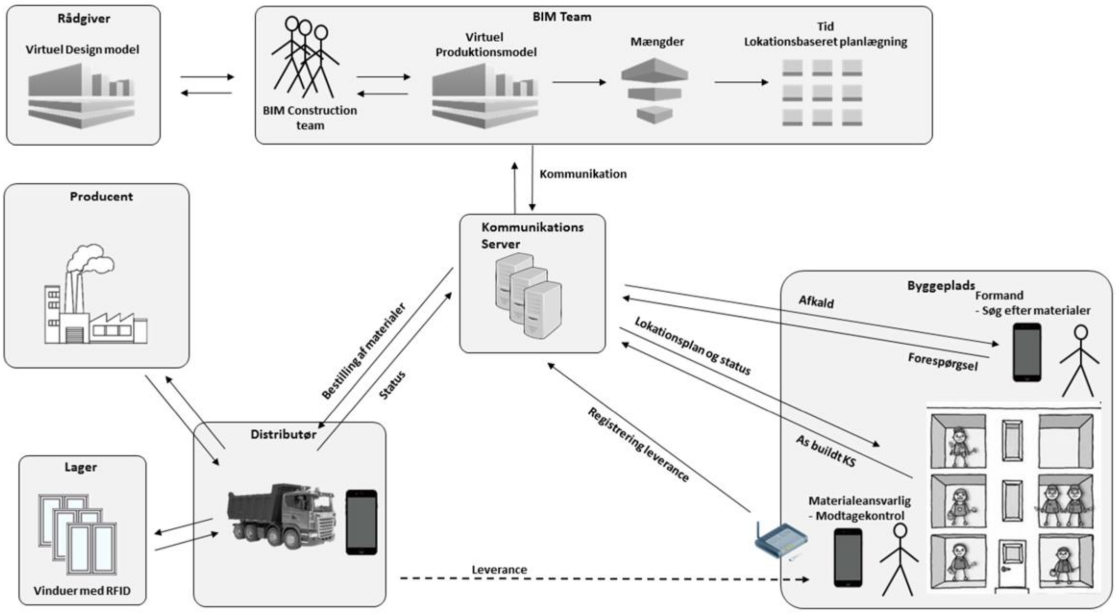

Figure 7: Logistics management process using RFID and LBMS (Nielsen 2016, p. 12)

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.

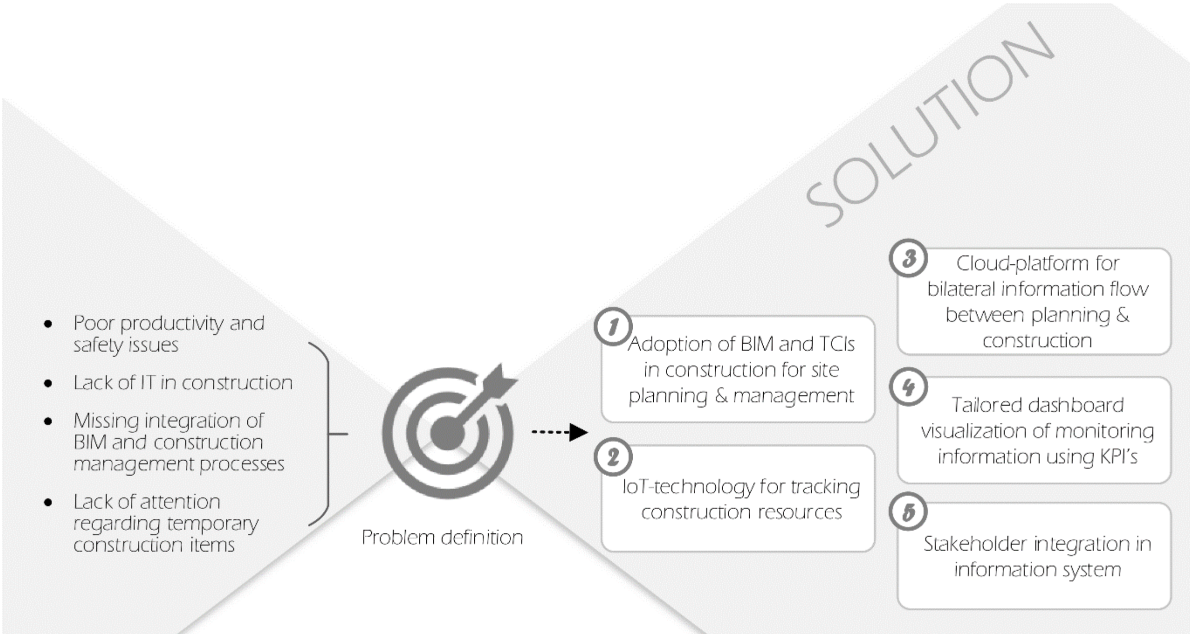

Figure 8: Findings from state of art solutions from the literature review (own visualization)

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.

A	Introduction to Interviewees (Group A) – Verifying Literature Findings		Experience
1	Consultant 1	Client Advisor at Exigo A/S	+ 5 years
	Value-added	• 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	
2	Consultant 2	Head of Digitalization at Consultancy A	+ 15 years
	Value-added	• Implementation of productivity-enhancing tools for construction • Knowledge about current & future use of technology in construction • Project leader of numerous VDC projects	

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.

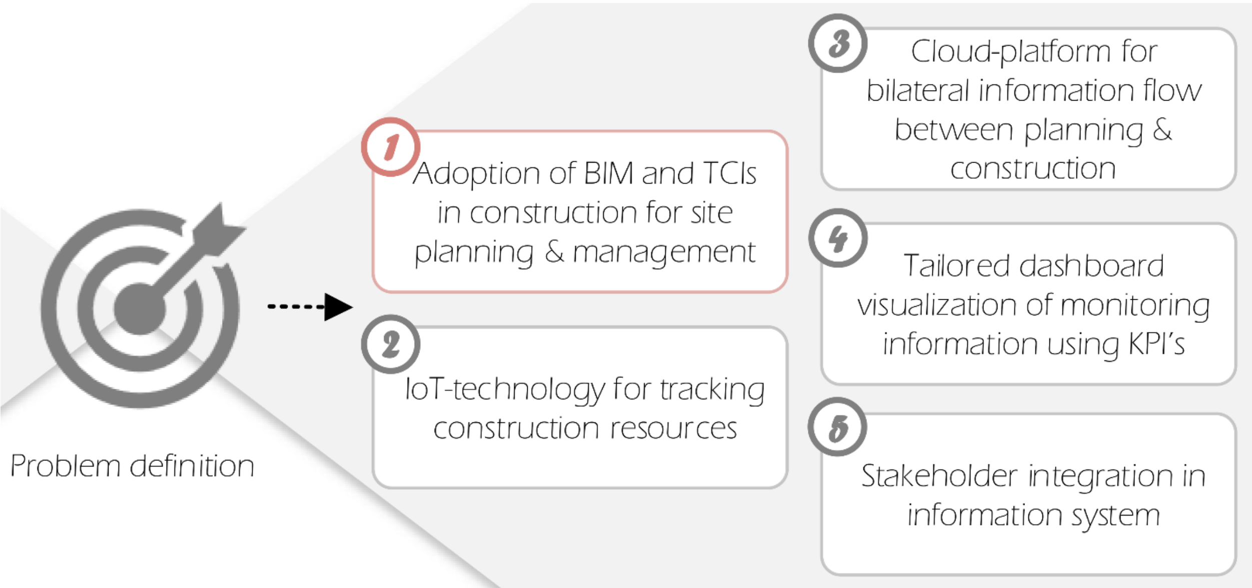

Figure 9: Focus areas of the solution space (Primary focus in red) (own visualization)

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

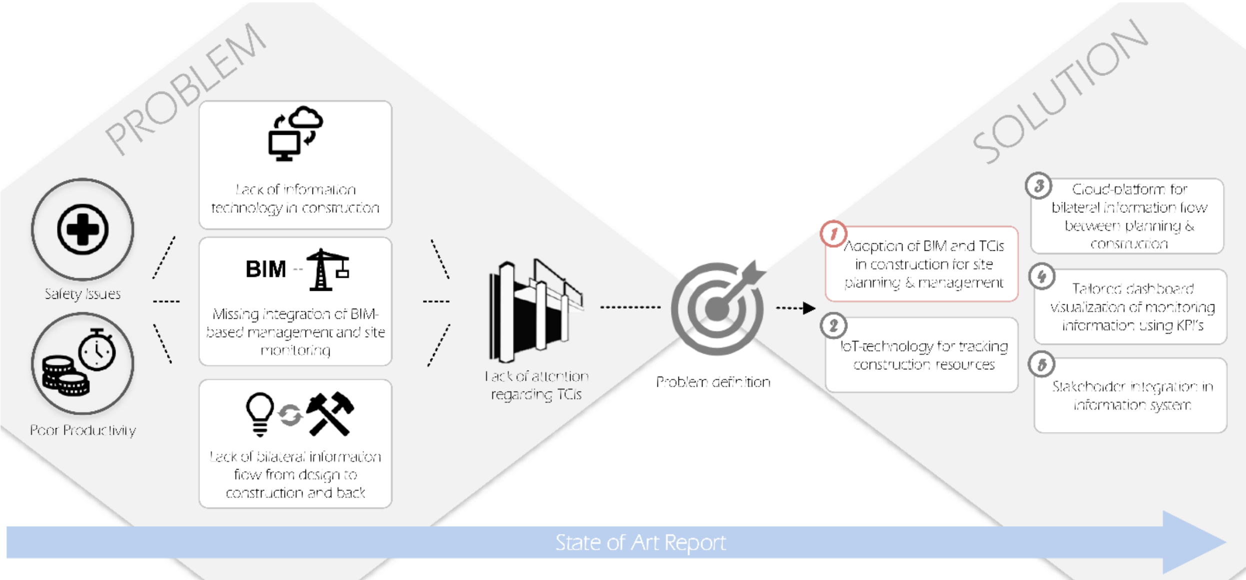

Figure 10: Overview of findings from chapter 2 (own visualization)

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.

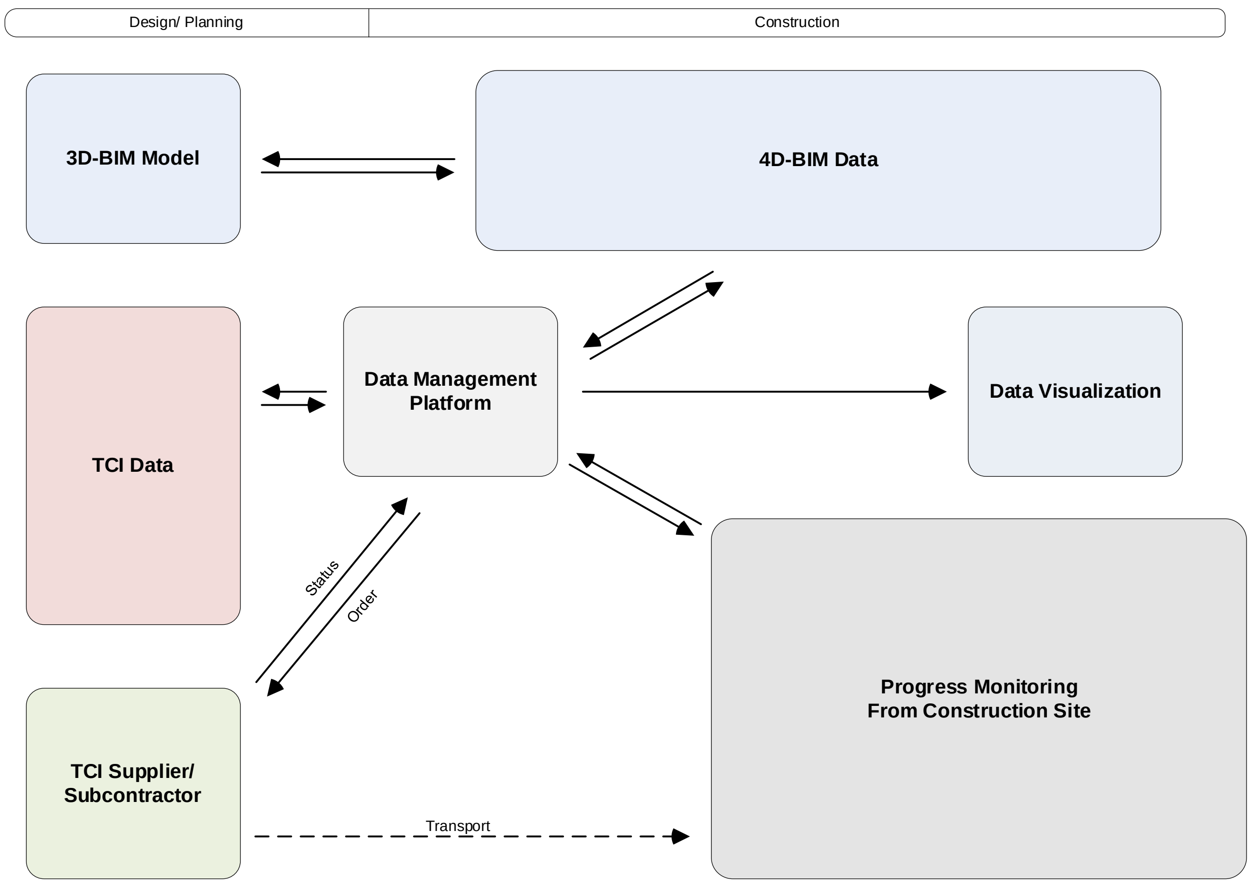

Figure 11: High-level framework of the innovative TCI management (own visualization)

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.

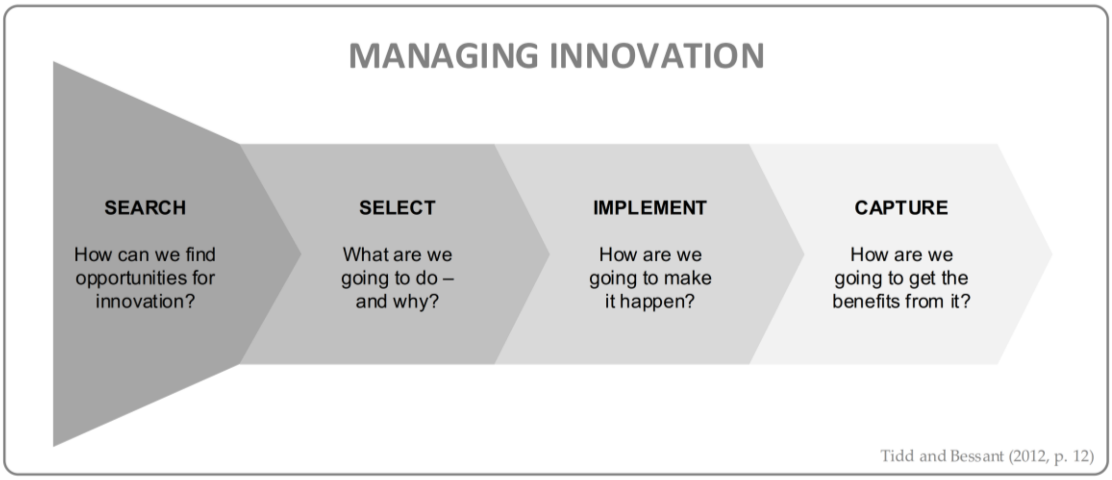

Figure 12: Model of the innovation process (own visualization)

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.

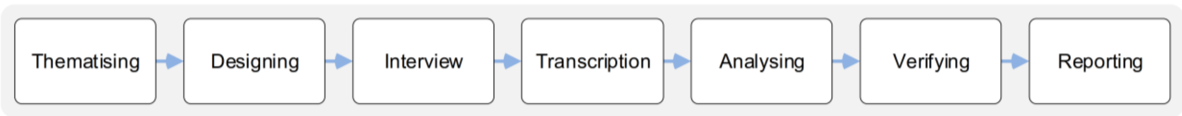

Figure 13: The seven stages of an interview investigation (own visualization)

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.

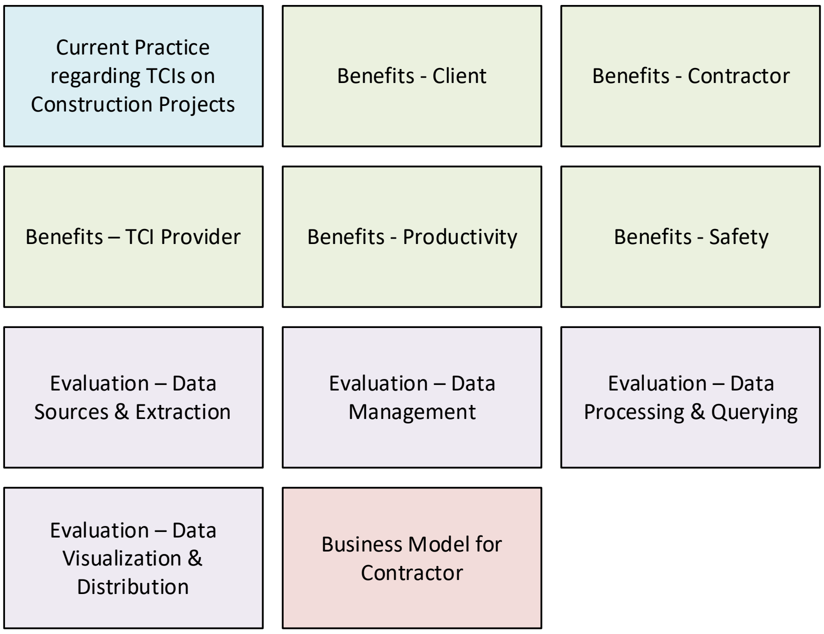

Figure 14: Deductively developed categories for content analysis (own visualization)

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).

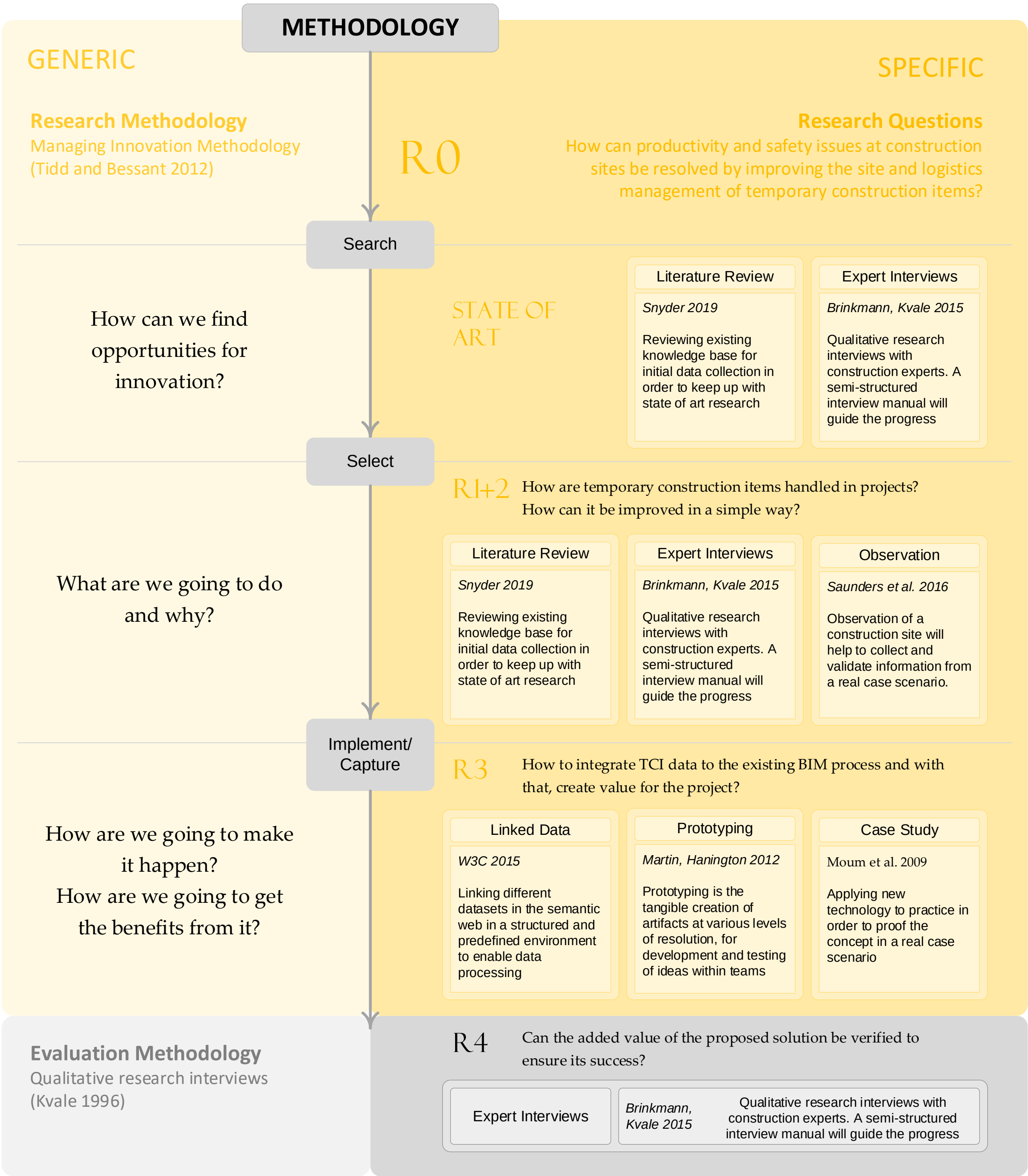

Figure 15: Research methodology and derived methods (own visualization)

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	m²
Disassembly of formwork	m²
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 .

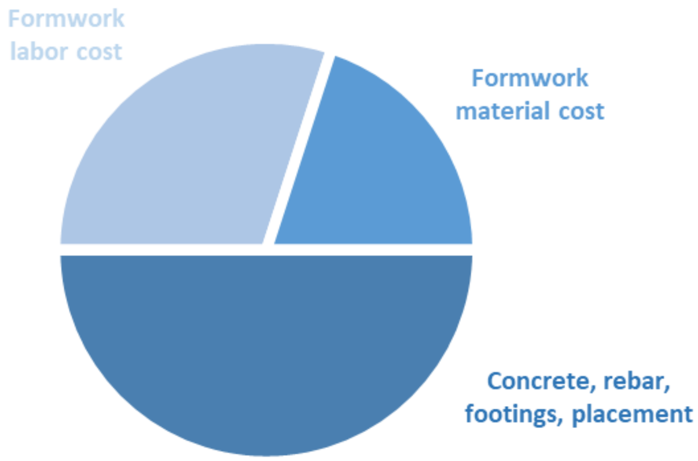

Figure 16: Costs of erecting a concrete building part (own visualization)

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.

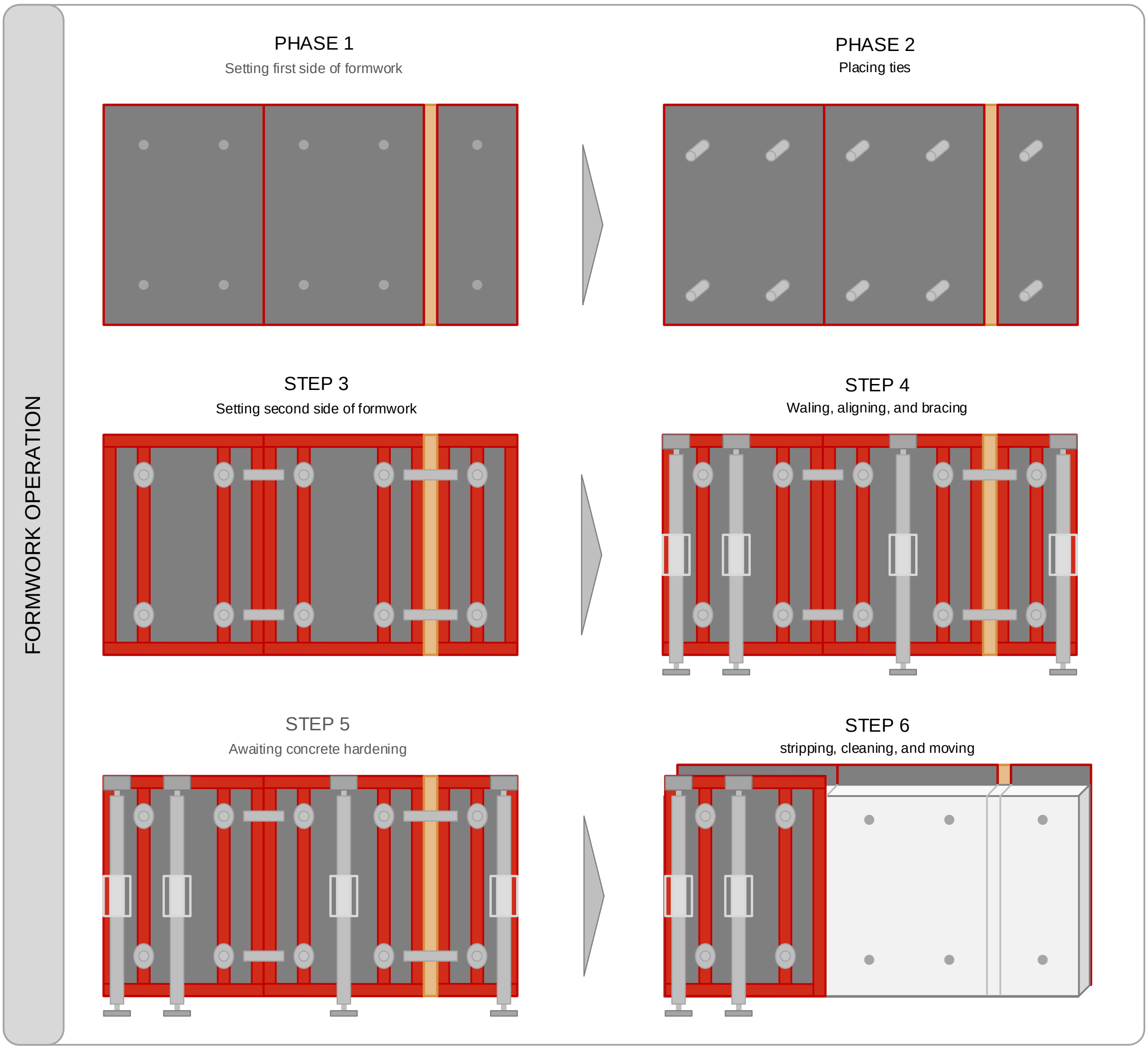

Figure 17: Formwork operation in 6 phases (own visualization)

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.

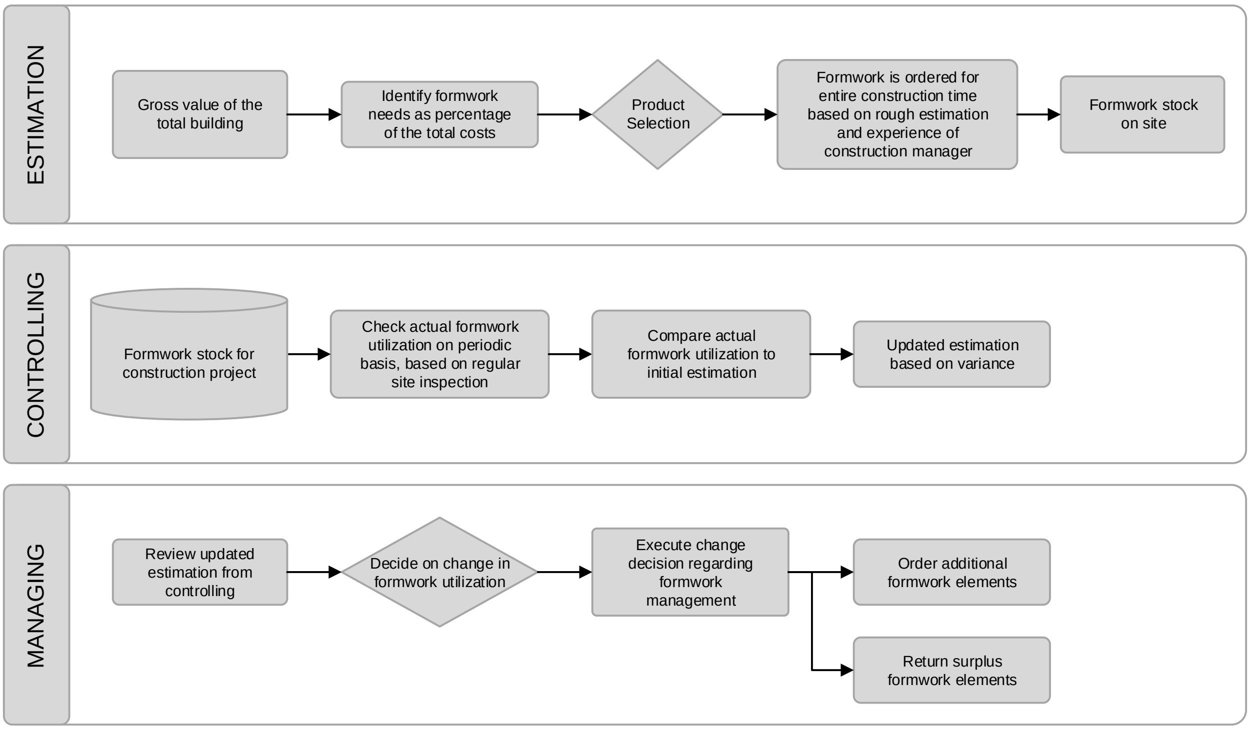

Figure 19: Formwork estimation, controlling and management (own visualization)

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:

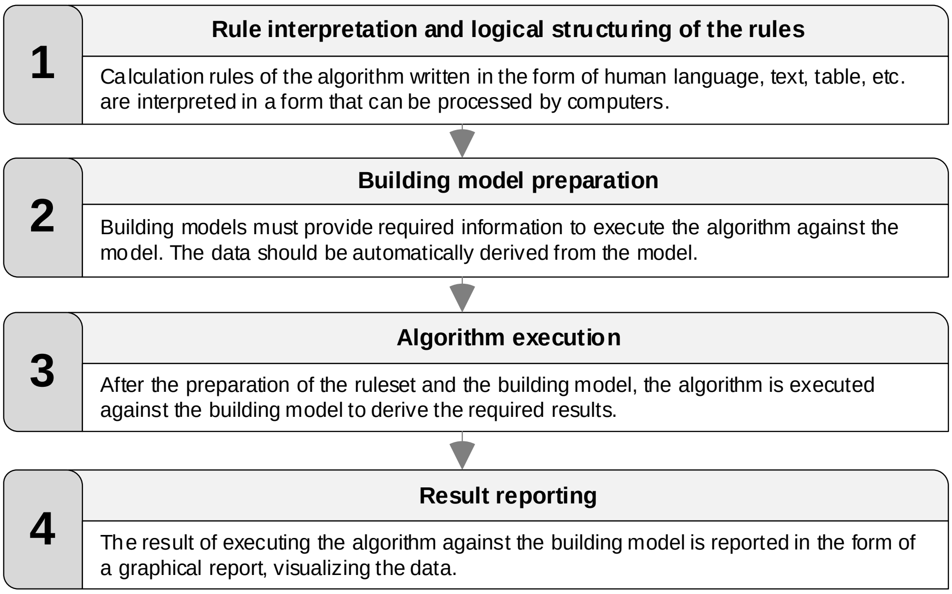

Figure 20: Steps of developing an algorithm for automatic TCI planning (own visualization)

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.

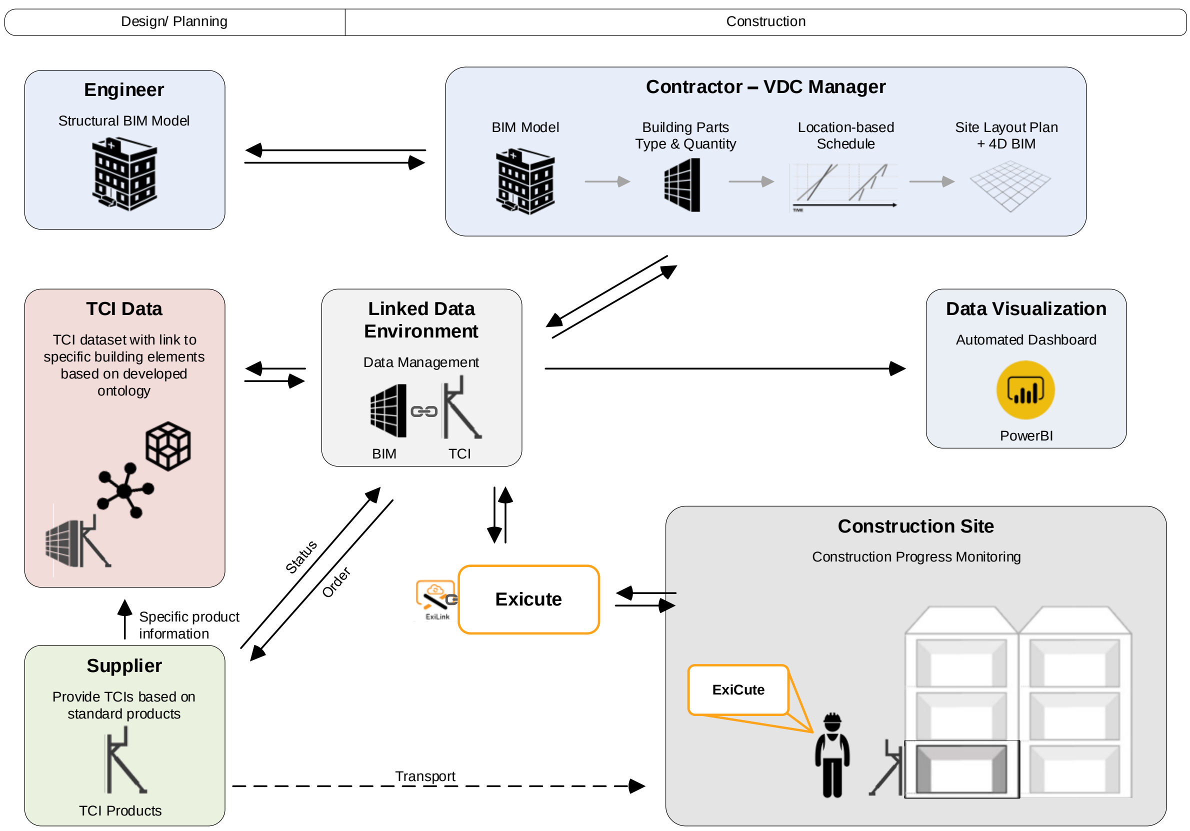

Figure 21: Proposed framework for the innovative TCI management (own visualization)

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.

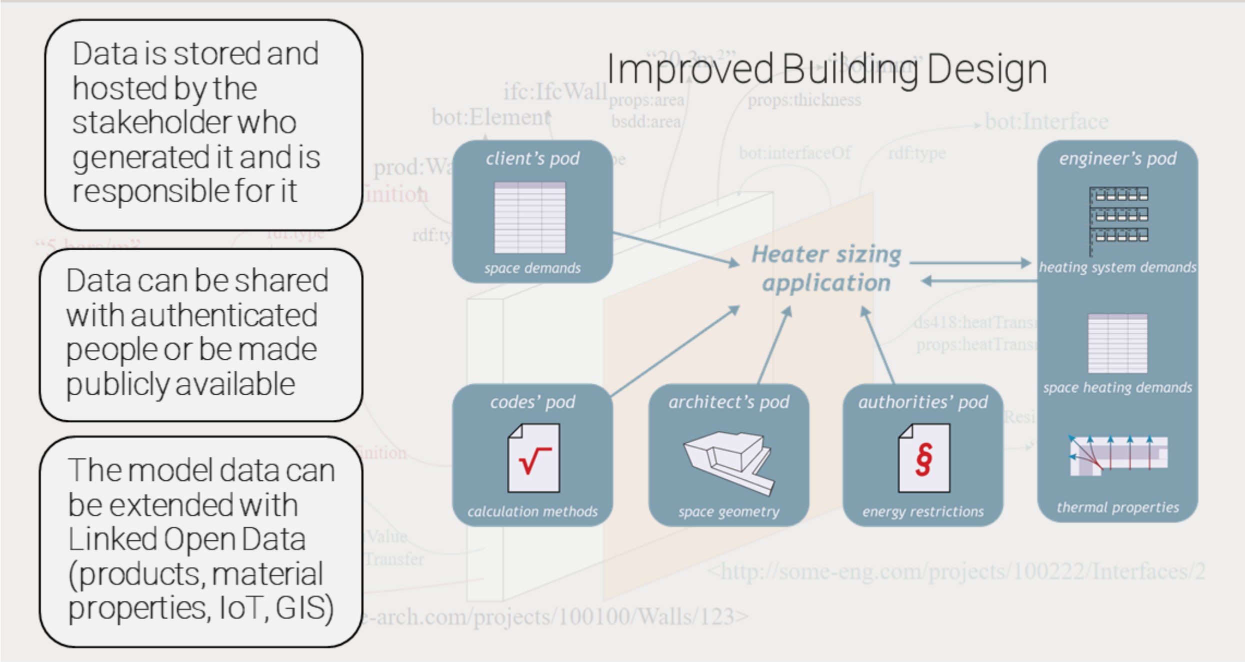

Figure 22: Linked Building Data - Heater Sizing Example (Rasmussen 3/5/2020)

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).

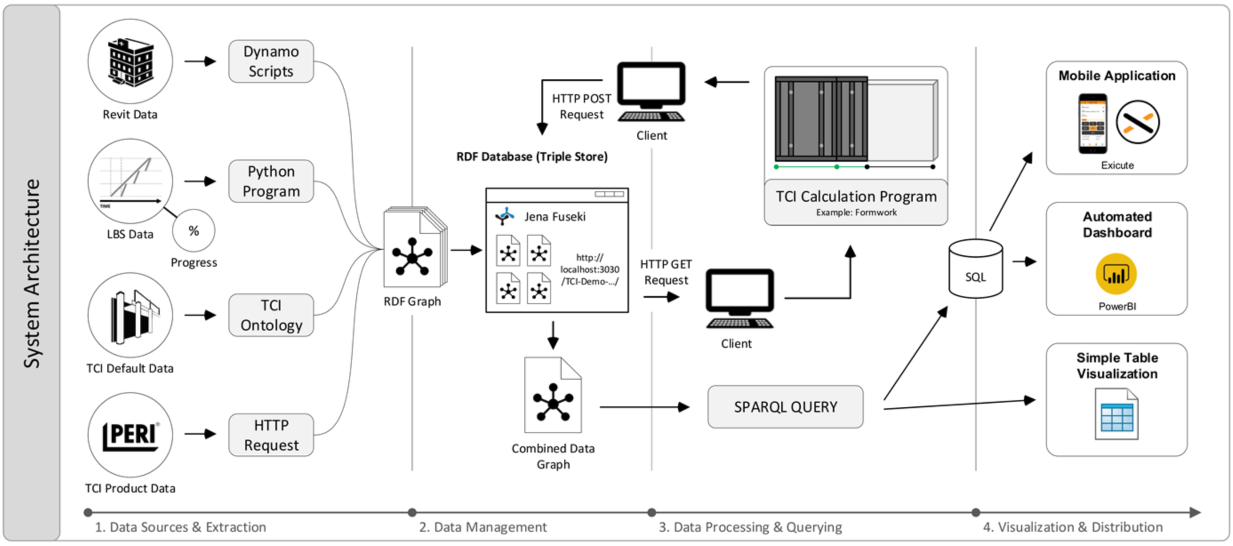

Figure 23: System architecture of the proposed solution (own visualization)

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.

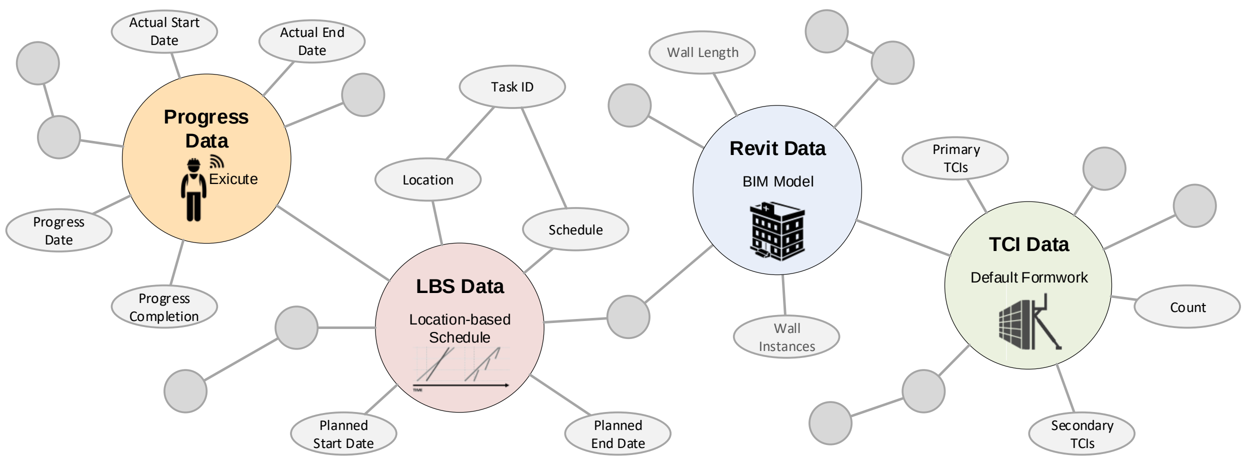

Figure 24: Datasets with contributed information (own visualization)

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.

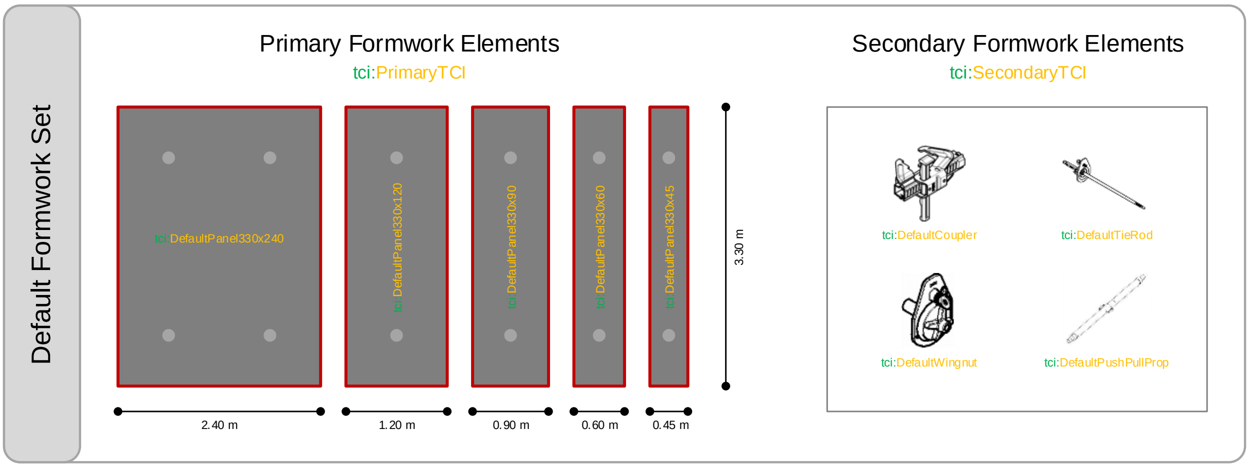

Figure 27: Default Formwork Set (own visualization)

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.

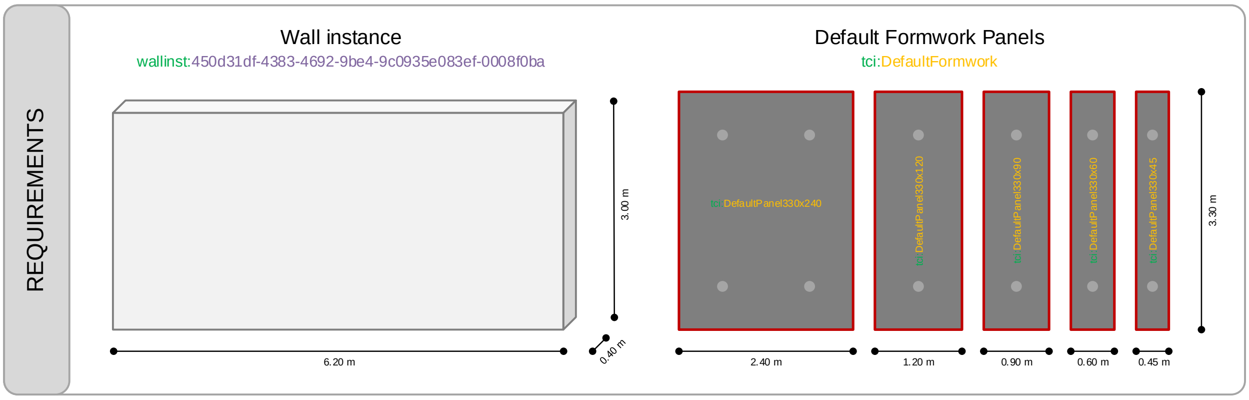

Figure 28: Data input for calculating the formwork demands (own visualization)

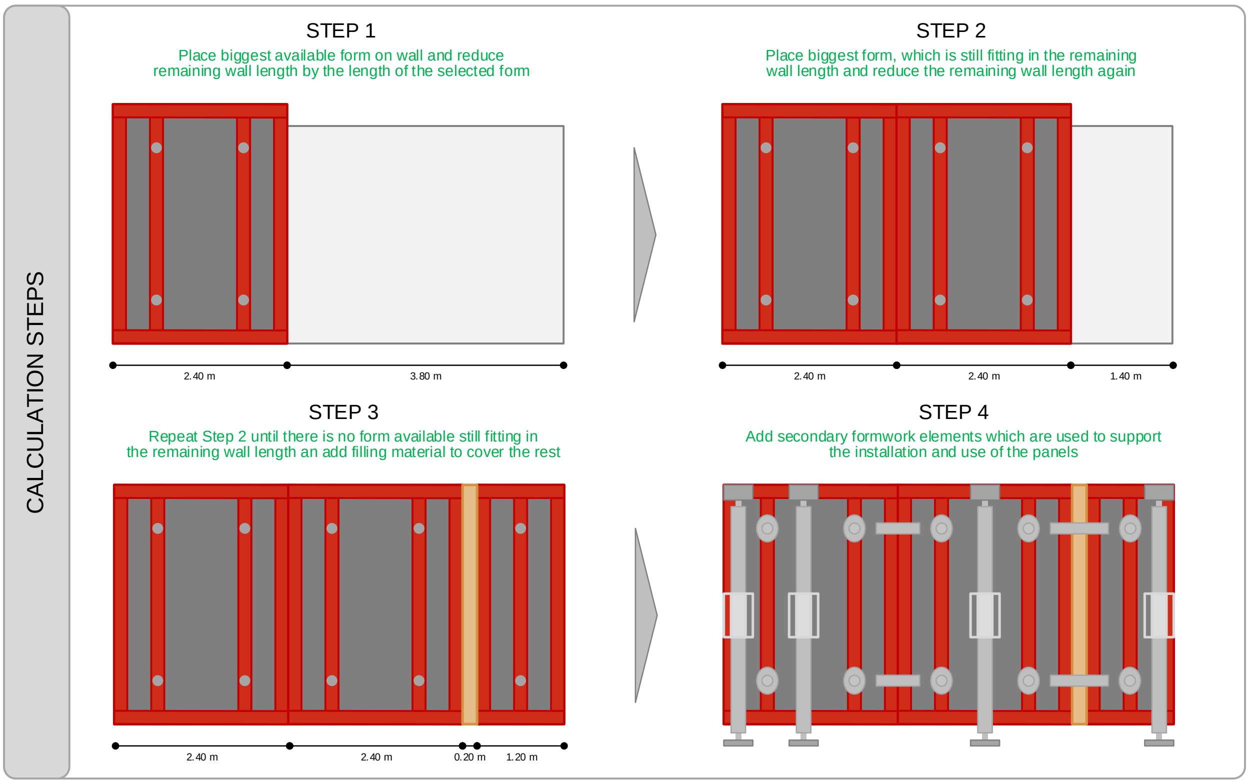

Figure 29: Consecutive steps of the formwork calculation (own visualization)

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.

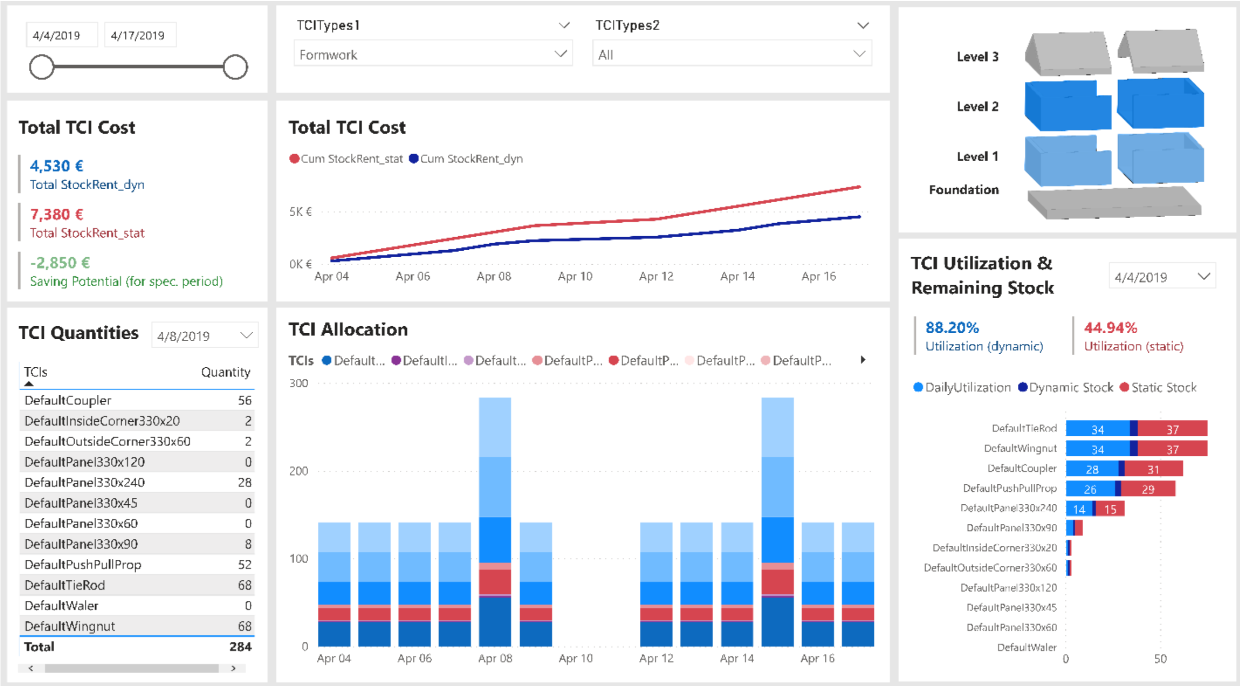

Figure 31: Visualization Tool 1 - Power BI Dashboard *TCI Utilization* (own visualization)

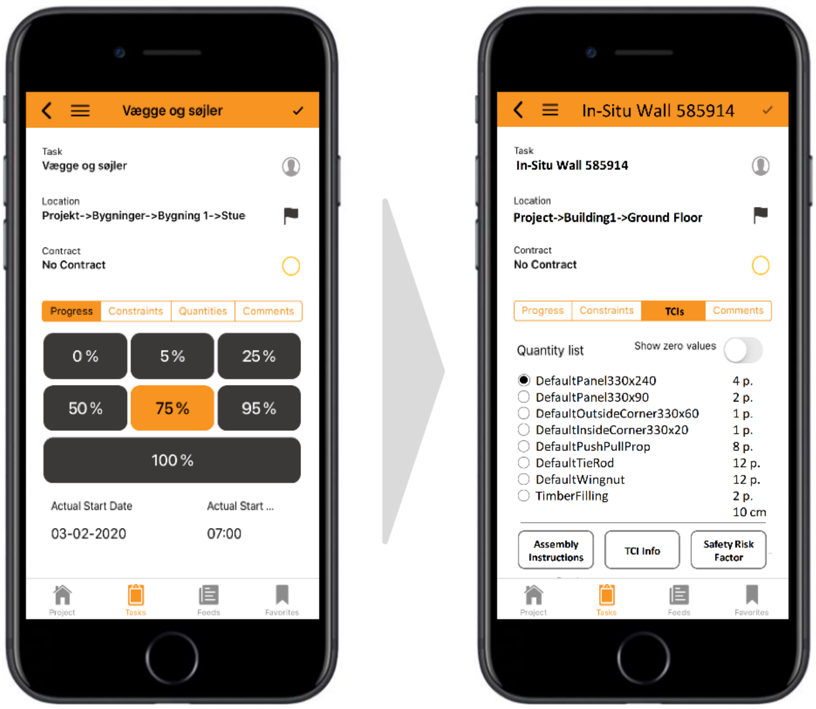

Figure 32: Visualization Tool 2 - New tab in Exicute application (own visualization)

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.

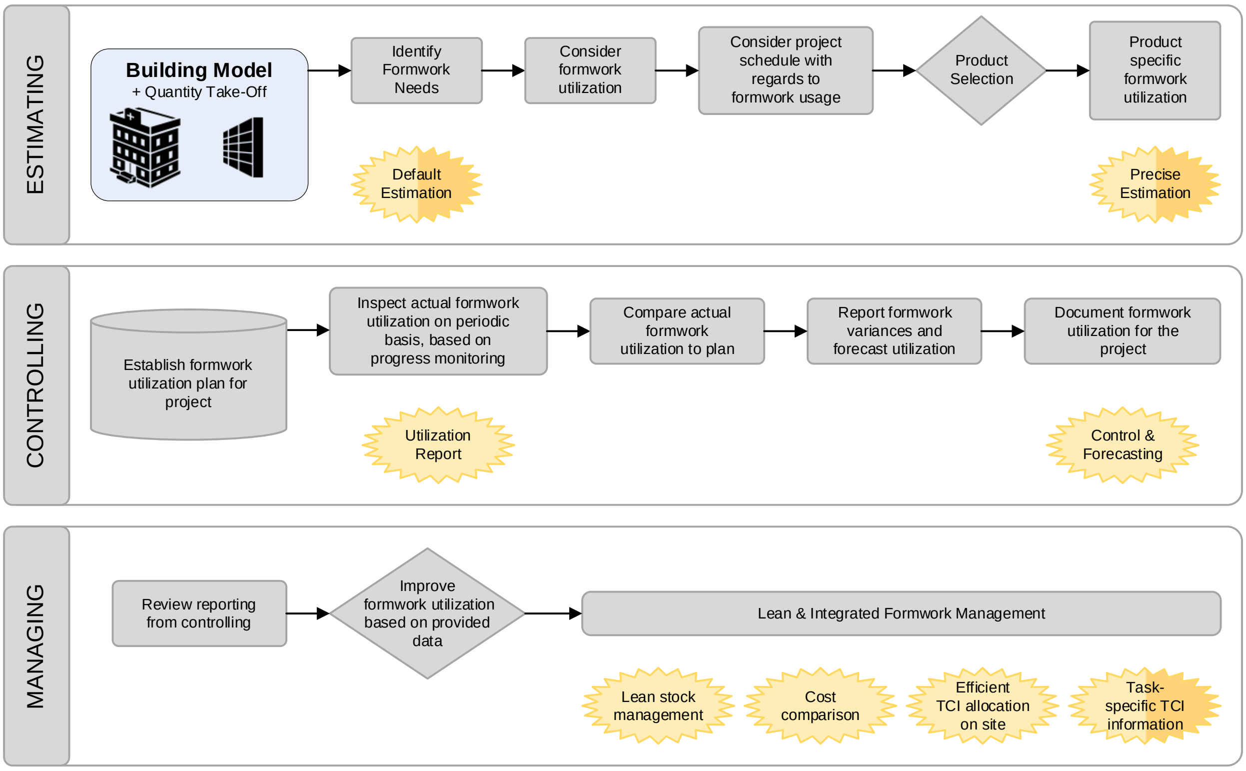

Figure 33: Revised process flow the formwork utilization (own visualization)

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).

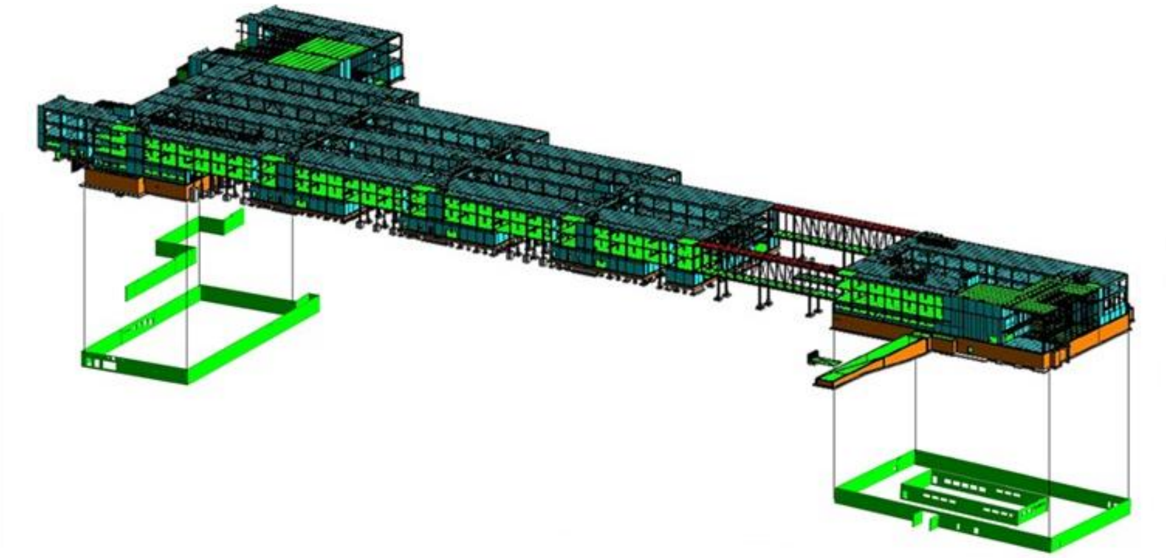

Figure 35: Revit model of the case project with the regarded in-situ walls (own visualization)

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.

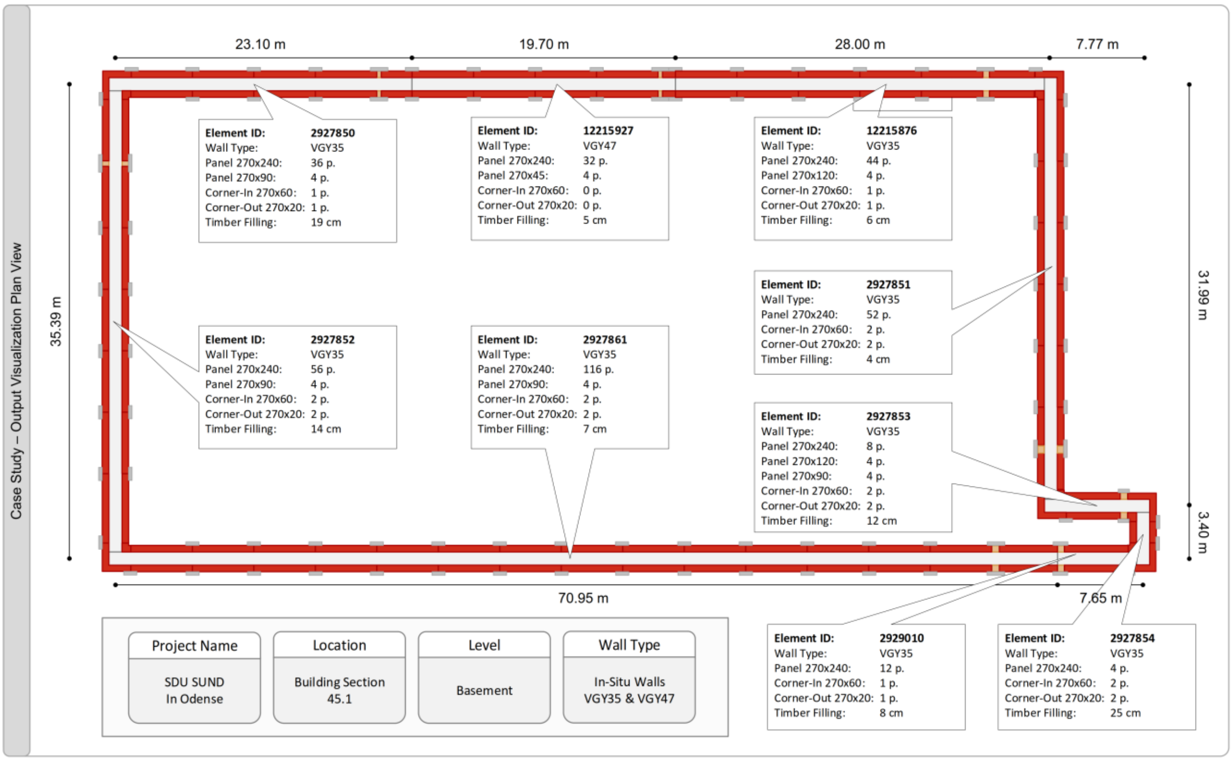

Figure 36: Output visualization plan view (own visualization)

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)

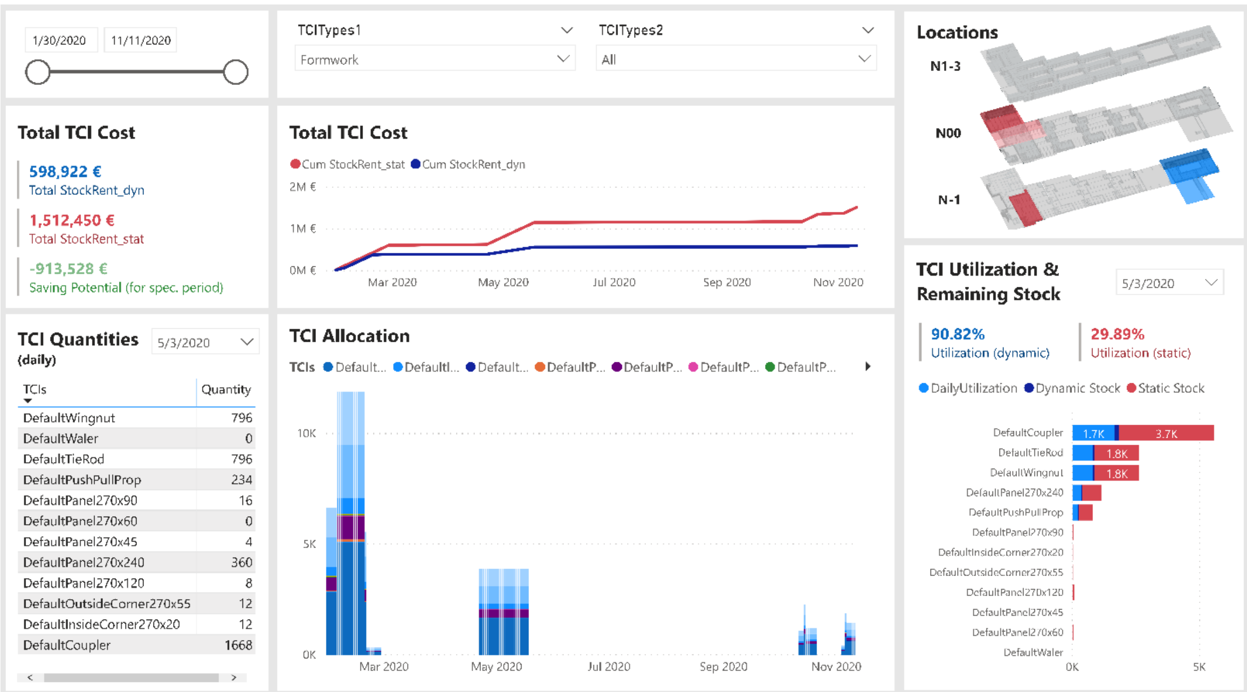

Figure 37: Dashboard Page 3 – *TCI Utilization* (own visualization)

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.

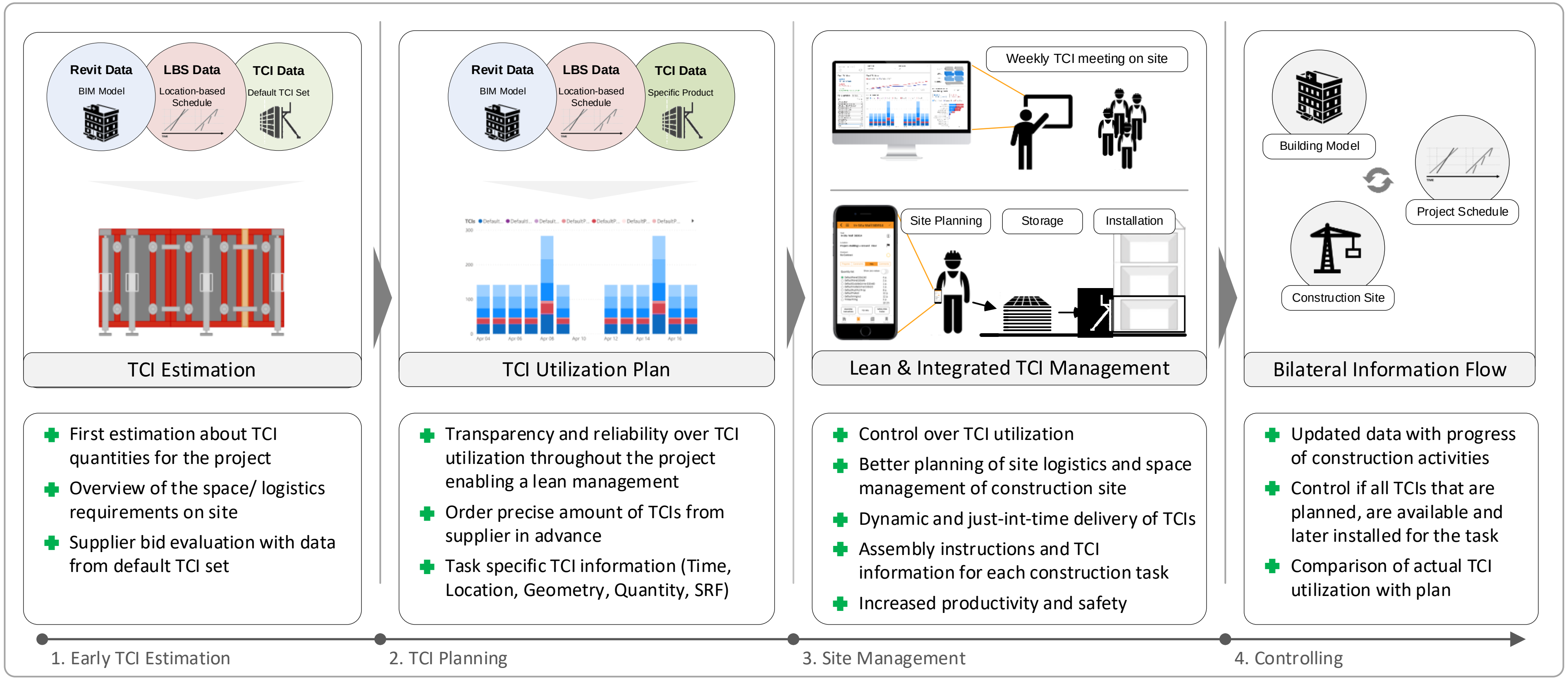

Figure 38: Process integration of the proposed solution with benefits (own visualization)

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.

Information for Project Manager | Information for Construction Worker

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.

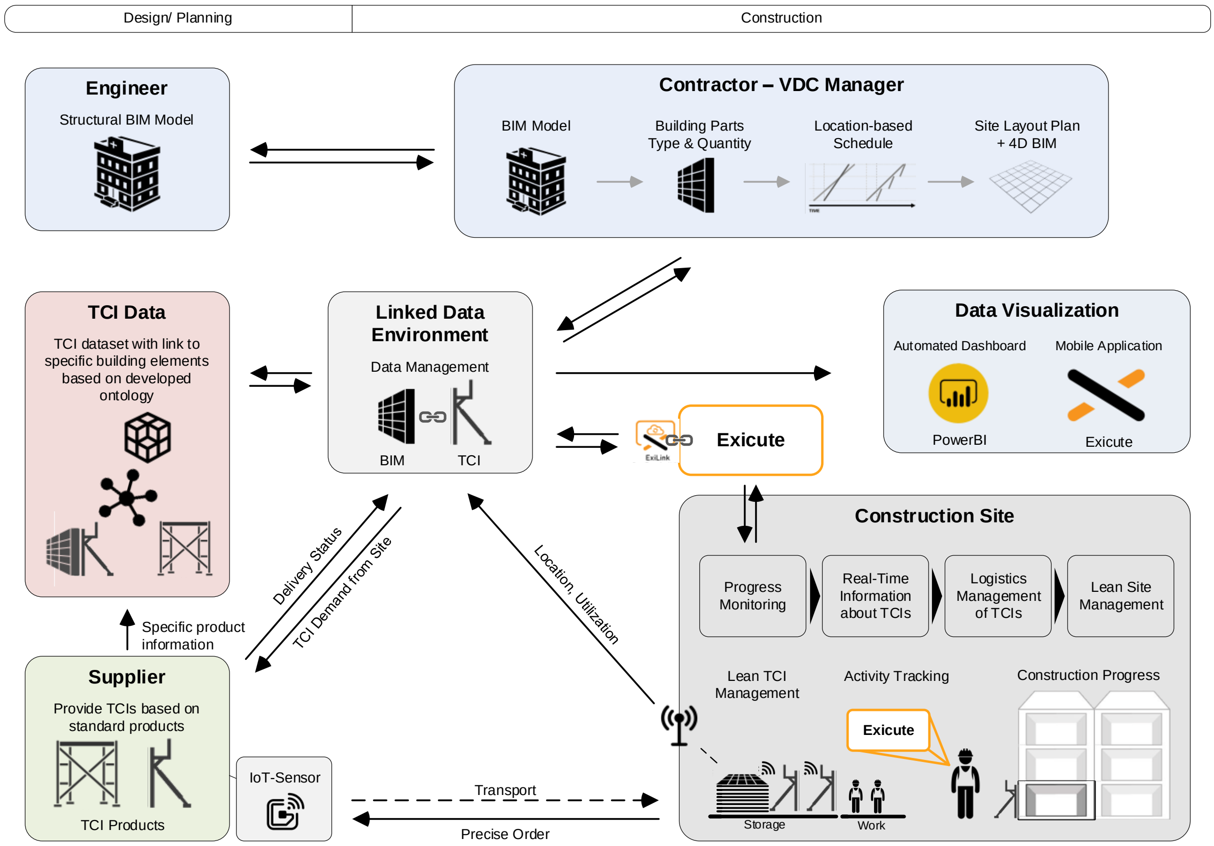

Figure 40: Framework for the implementation in the current industry (own visualization)

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.

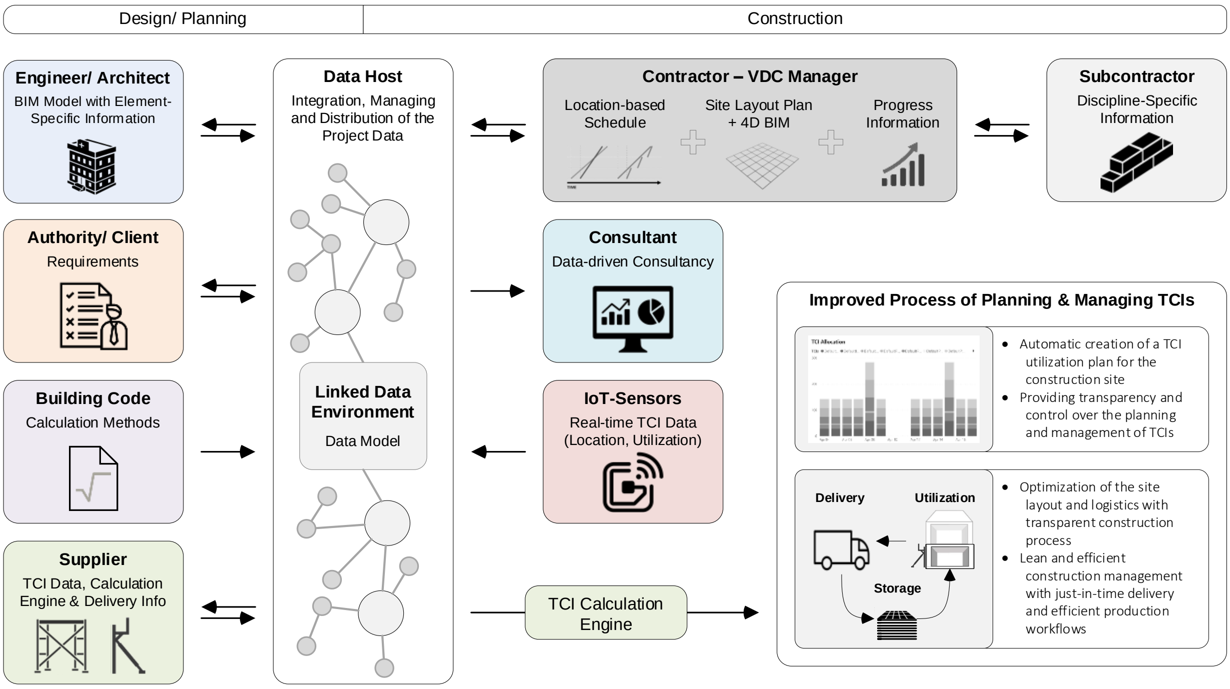

Figure 41: New framework with a new project delivery system (own visualization)

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.

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Appendices

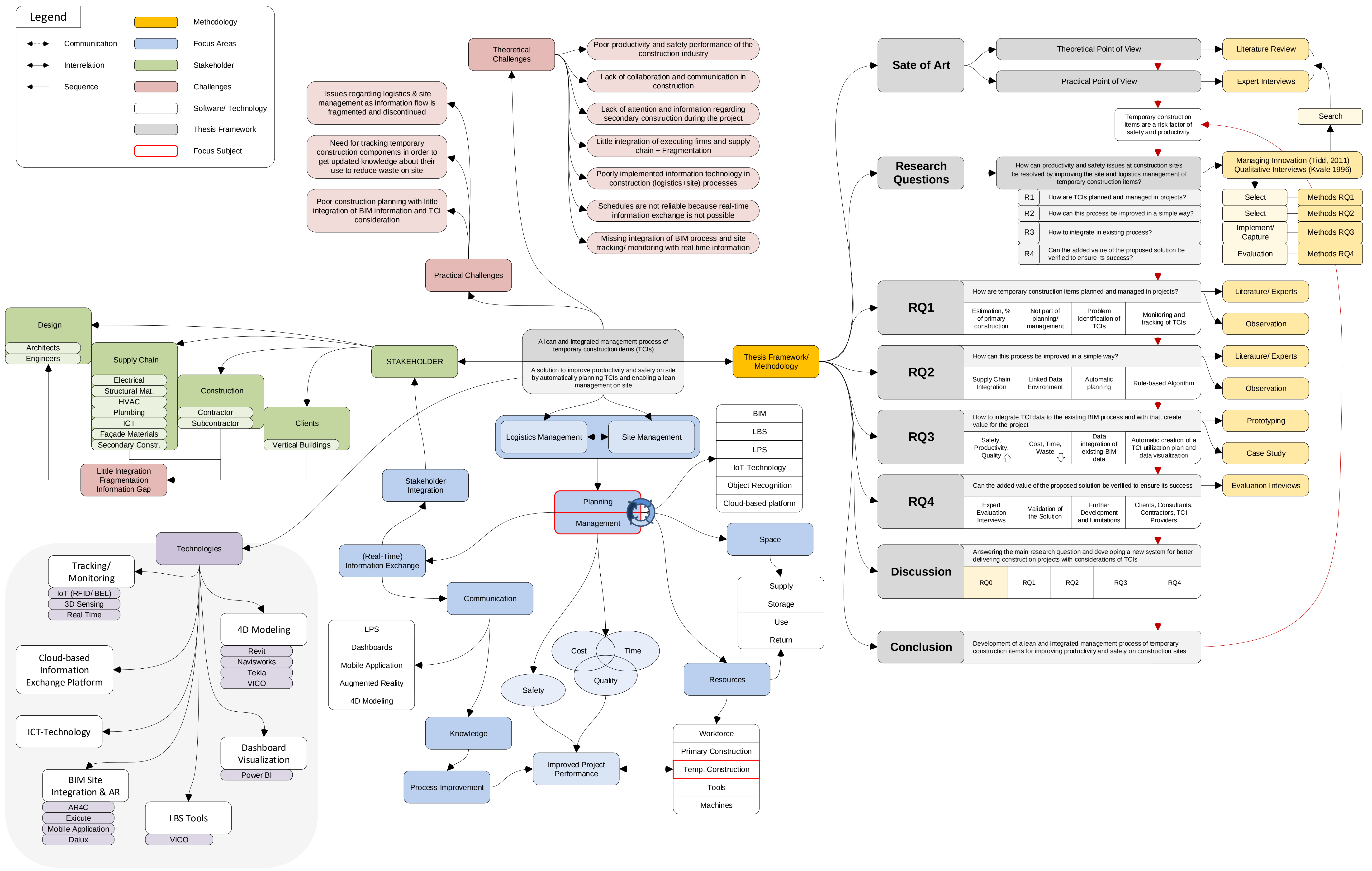
Appendix 1:	Scope of the Thesis
Appendix 2:	Photo Documentation
Appendix 3:	Demo Project Documentation
Appendix 4:	Case Study Documentation
Appendix 5.1:	Interview Guide for State-of-Art Report
Appendix 5.2:	Interview Guide for Concept Development
Appendix 5.3:	Interview Guide for Evaluation Interviews
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

Appendix 1

Scope of the Thesis

SCOPE OF THESIS | A LEAN AND INTEGRATED MANAGEMENT PROCESS OF TEMPORARY CONSTRUCTION ITEMS (TCIS)

Technical University of Denmark



Appendix 2

Photo Documentation

Photo Documentation of Site Observation (06.04.2020)

In order to validate the potential of a process improvement in the field of interest of this thesis, an actual construction site is observed with the goal to identify drawbacks and waste in current practice regarding the management of TCIs.
Using a participant observation role allows to observe current practice regarding TCIs (Saunders et al. 2016) and includes both own experience and the experience of the project participants regarding the research selection for verification purposes. The semi-structured interview with the construction professionals is regarded in chapter 5.1.1 while this photo documentation will reflect the observation which was conducted during the site visit. The photos represent the situation on site and will be used to identify current practices and how the proposed solution might improve these situations.

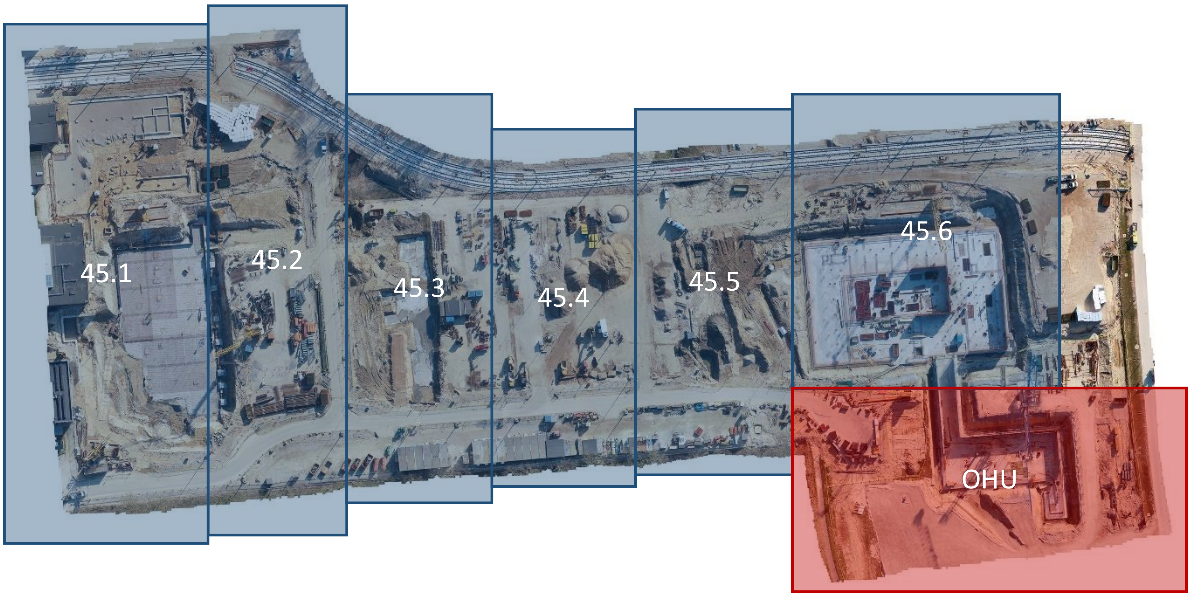


Figure 1: Construction site drone picture with different locations

N.	Photos	Comments
		Site facilities are located on a strip, where no construction will happen. There is enough space available to provide site facilities at this location for the entire construction project. In general, the site facilities are well planned and there is a site layout which specifies the bigger installations on site as cranes, container, etc. **Potential**: TCIs that are not directly related to the construction activities, as office container, might be calculated with the total quantities of the building and the schedule information.
1	Site facilities near the entrance of the construction site	

N.	Photos	Comments
		Different standard forms, that are rented from a supplier are located at the storage area. **Potential**: An updated and detailed utilization plan of the formwork might enable a more "just-in-time" delivery as well as a dynamic planning and lean management from delivery overutilization to the return of TCIs. This will benefit all parties involved in the TCI-cycle for a construction site.
2	Storage area of formwork that is currently not used	
		Single form laying around which might block the access to other items at the storage area. **Potential**: 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.
3	Single form laying on the floor, blocking useful storage area	
		This picture shows the ongoing construction of the concrete walls in the basement. Formwork is used to support this activity. In the front, electric cables are placed in an earth route to enable electrical service on site. **Potential**: With the proposed solution, the construction manager would at all times have transparent knowledge about what types and quantities of formwork is used in which location of the construction site.
4	View to the construction of basement walls with electric cabling in the front	
		Metal plates are used to create a temporary road that enables transportation on site. Signage-posts are used to mark the way. Next to the road, a neglected form was noticed. **Potential**: TCIs, related to on-site transportation can be part of the solution as long as there is a site-layout model, enabling a relation of TCIs to a model object. There would not be a neglected item on site and IoT-tracking of TCIs would further improve the transparency.
5	Temporary construction road using metal plates and way signage	

N.	Photos	Comments
		Different building material and TCIs are located on the foundation. The quantity of the located forms should fit the need for constructing the walls. There shouldn't be too few and to many forms to still be able to provide sufficient support for the construction activities but not blocking the limited space and costing rent. **Potential**: Quantities are available on a detailed level for each activity, enabling a lean management of the items on site.
6	Basement foundation with ongoing casting of in-situ concrete walls	
		Installed formwork that supports the construction of a basement wall. Secondary formwork parts as push-pull props, walers, couplers, etc. are clearly visible. **Potential**: Secondary formwork parts can be calculated for each construction activity with a simple estimation that is based on the panel quantities and sizes.
7	Formwork installation for basement walls	
		Several temporary construction items are laying around, near an ascent from the excavation area. It is assumed that the storage area is not official and there might not be a record or documentation of the location of the shown items. **Potential**: If TCIs are planned with time and location information throughout the construction project, one will always have knowledge where the items are supposed to be.
8	Temporary construction items on site	
		A foundation reinforcement is placed at basement level. Formwork elements are stored temporarily on the reinforcement and it is unclear where the forms belong to. **Potential**: A construction manager can easily compare the planned quantities of TCIs with what is installed on site, identifying missing parts. Having IoT-tracking of these items will also allow to locate the required items for each construction activity if not stored properly.
9	Formwork elements laying on foundation reinforcement	

N.	Photos	Comments
		Several temporary construction items are laying around a storage area. These small storage areas allow a lean storage of TCIs near the location where they are used next. With current practice, it is however unclear, if the stored elements are sufficient for the upcoming tasks. **Potential**: Specifying decentralized and dynamic storage areas on site allows to store the TCIs where they are easily accessible for the next utilization without blocking other construction processes on site.
10	Storage area for different items	

Concluding Comments

The observed construction site of the new SDU SUND project is generally managed and planned well, especially regarding site facilities as container offices and main storage area near the entrance of the site. Furthermore, all machines as cranes and lifting platforms are in place and intact.

However, there have been issues with planning TCIs on site as they were not considered in the initial plan and budget. Fences for separating construction roads and walkways were not planned and budgeting of other TCIs is only estimated as a part of the total construction costs but never broken down to a more detailed level. This is also reflected by the photo documentation, which shows several items that are just laying around the construction site, blocking access paths or causing safety hazards for the construction workers. This little attention regarding TCIs is a common practice for several construction sites.

The proposed solution in this thesis is taking this issue into account and tries to automate the planning, management and monitoring of TCIs on site by linking them to the existing building model and project schedule. For formwork, scaffolding and supporting beams, the relation between the TCIs and building objects is obvious but also TCIs as road signage, safety fencing or metal plates can be included in the solution as long as there is a site layout model available. Based on this model and the respective schedule information, the number of TCIs which are needed to support a specific phase of construction activity can be calculated with an algorithm and then linked to the model elements. With this approach, the developed algorithm can be applied to almost all construction projects as the way of calculating TCIs is the same, either based on best practice or specified in commonly used standards.

The conducted observation of the construction site, on the one hand, presented an already well managed and modern construction site, but nevertheless revealed space for improvements regarding the planning and management of TCIs. On the other hand, the assumption was verified, whether the project fits as a case study to test the proposed solution. The developed prototype solution focuses on planning and management of formwork and hence, the main requirement for that is the utilization of formwork. As shown in the photo documentation, this is the case at the SDU SUND project in Odense. The case study will then reveal the real potential of the solution by allowing a comparison between the practice without and with the proposed solution.

Appendix 3

Demo Project Documentation

TECHNICAL UNIVERSITY OF DENMARK

PROTOTYPING – Demo Project Documentation

APPENDIX 3

Thesis:	Unlocking the value of Linked Building Data (LBD) - A Lean and integrated management process of temporary construction items (TCIs)
Chapter:	Chapter 6.1 – Demo Project (Input for RQ3)
Method:	Prototyping (Martin & Hanington, 2012)
Purpose:	This demo documentation will serve as a protocol for the prototyping process of the proposed theoretical solution in the thesis. The documentation is structured to follow the consecutive steps of prototyping and spans from the creation of the demo-project-specific BIM data, over the data extraction and translation into an RDF-based knowledge graph to the data processing and to receive the required results.
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Student number:	182781

Table of Content

List of Figures

List of Tables

Chapter 1. Introduction

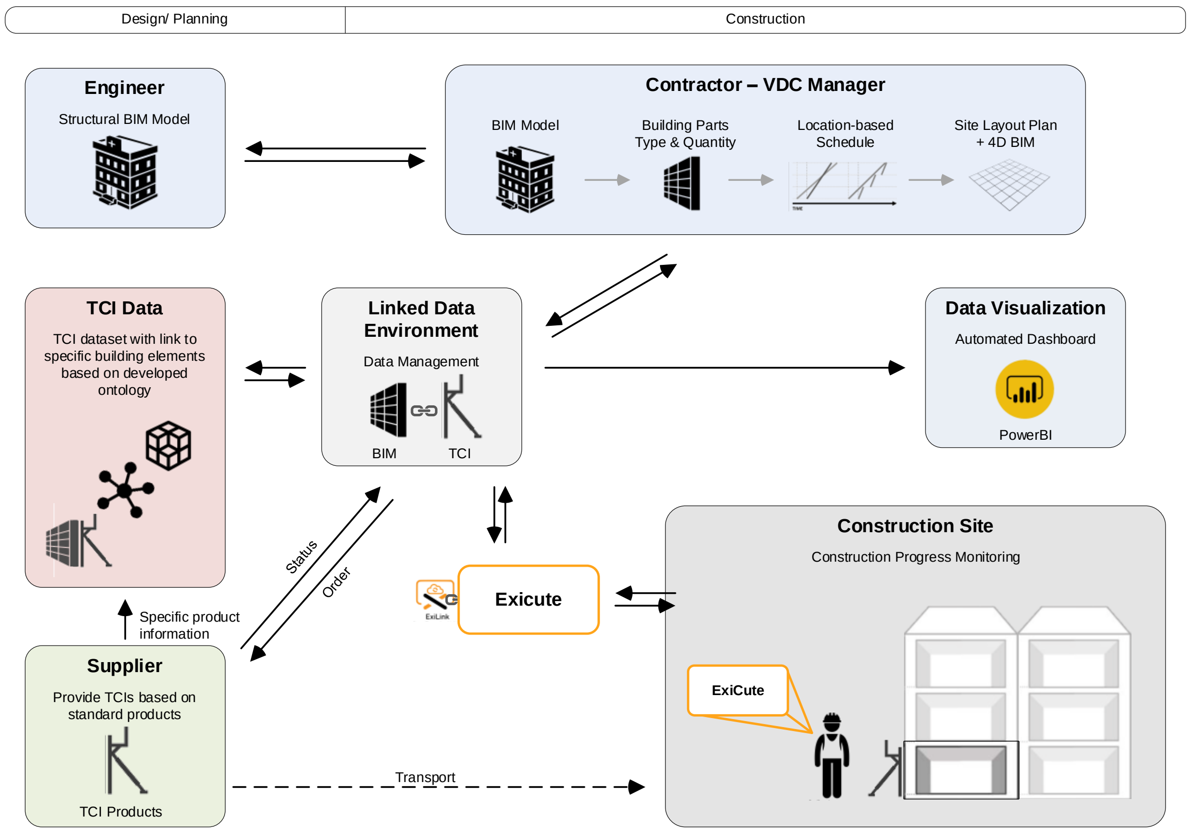


Figure 1: Proposed framework for the innovative management process of TCIs

The Demo Project is part of the prototyping methodology and is used to validate the proof of concept of the proposed solution with a small-scale and fictive building project. The same workflow and the same tools are used as in a real project to create all required data and receive the required output data. As a result of the prototyping process, a functioning system shall be developed that is able to improve the logistic management process of TCIs in a construction project, visualized in figure 1. Recapping the statements in chapter 5.2.1, the overall goal of implementing the proposed solution is to: (a) automatically evaluate the building model geometry, (b) identify required TCIs to each building object 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 objects, their locations, and schedule, (e) enable a passive monitoring of the TCI items with progress tracking data and (f) visualize data automatically and interactively to all relevant stakeholders.

To realize this goal, an integrated system must be established that can receive all required datasets, bring the data in the required and structured format and in the end link the datasets to one combined data graph where the data can be processed in order to receive the needed results. The methodology for creating this integrated system is based on the semantic web and linked data approach that was introduced in chapter 5.2.2. Linked data is enabled by the data model RDF (Resource Description Framework). RDF data is stored in a data graph that consists of triples which are linked with relations and thus, creating an interconnected data network, a graph. 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, which is stored in RDF format.

Hence, the output data of the processed data in this project shall hold all information to create a TCI-utilization plan and by that manage and monitor these items throughout the construction project. Data visualization and distribution is considered the last step of the prototyping method and will provide the processed data in a user-friendly and visualized format, distributed to all relevant stakeholder groups. Figure 2 is summarizing the system architecture of the demo project and gives an overview of the consecutive prototyping steps to fulfill goals a) to f), identified earlier.

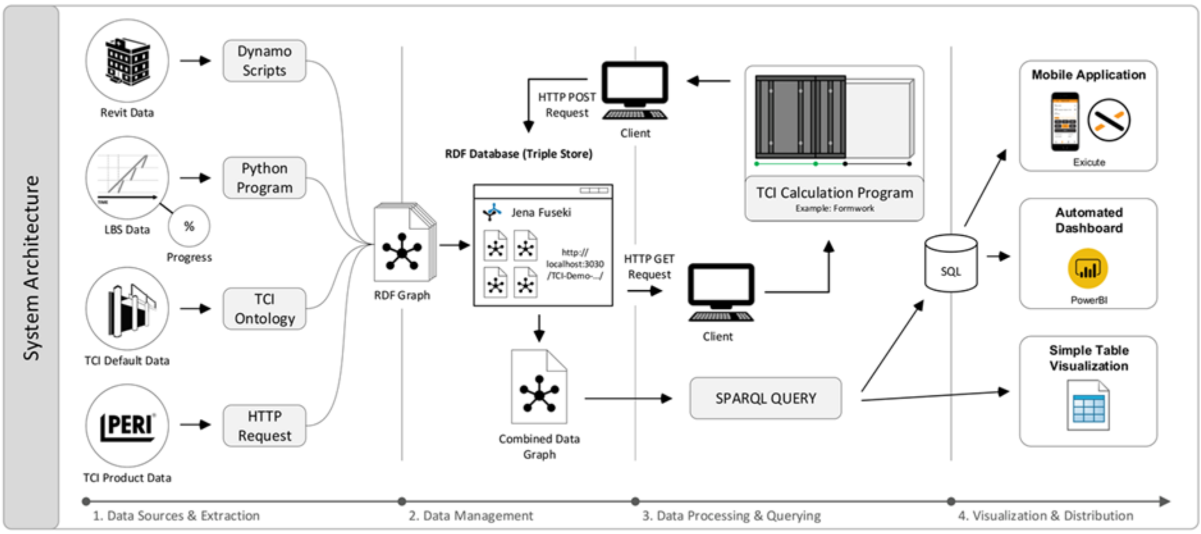


Figure 2: System Architecture of the proposed solution

Chapter 2. Data Sources & Extraction

2.1 Introduction to all data sources

For the demo project, a simple BIM project with a building model and schedule information is created. Walls are selected as a representative of building objects and formwork will represent the TCI-objects. Regarding the creation of the 3D model data and schedule data, common applications in the building industry are chosen. Autodesk Revit is used as the modeling software and VICO office as the complementary software to create a location-based schedule, based on the building elements of the 3D-Model. This schedule information is extended by a progress monitoring of the construction activity through the application Exicute (https://exicute.net/time-management/exicute-app/). The TCI data is generated by creating a new ontology that describes a default formwork set for the purpose of this demo project. The essential information which is needed from each data source is visualized in the following figure.

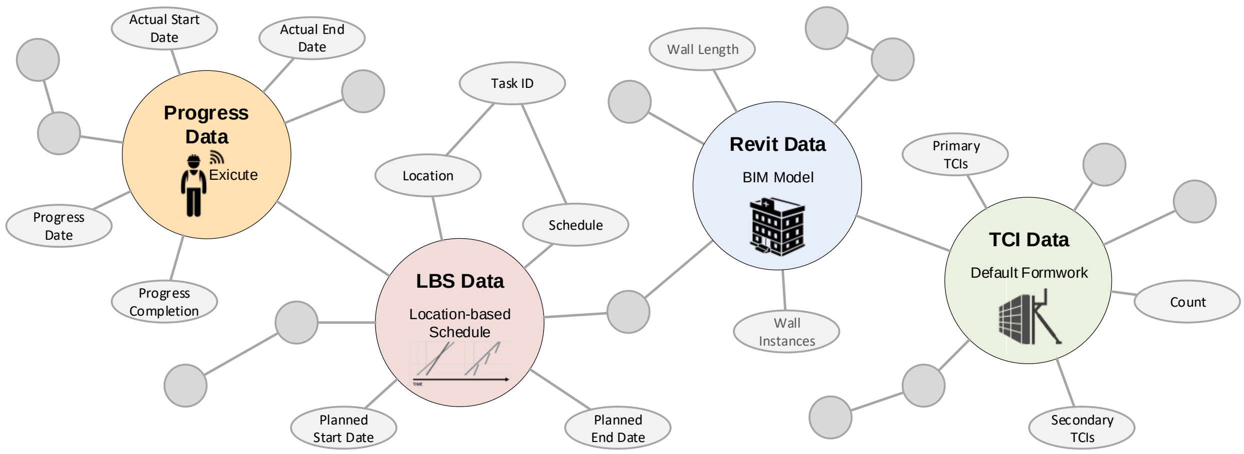


Figure 3: Data Sources with desired parameters

All four datasets are generated from different software applications and in different file formats. However, in the end, the data needs to be integrated into one knowledge graph and linked with previously created relations in the RDF triples. Therefore, the four different datasets need to be first converted into RDF triple files and then uploaded into an RDF triple store to create the respective data graph. Here, the open-source triple store Jena Fuseki is used to upload the different datasets into one database. In this triple store, the four individual datasets can then be integrated into one combined knowledge graph.

By then querying the linked data, the required results can be generated and used to improve the logistics management process of TCIs. This processed data can hence be visualized according to the stakeholders' needs in order to be used in real life.

2.2 3D-Model-Data

The BIM modelling software Revit 2019 is used to create a simple building model for the purpose of this prototyping. The model file name is "AS_Demo_Project" and contains a total of four levels (Foundation = Level 1, Ground Floor = Level 2, First Floor = Level 3, Attic = Level 4), a total of 14 walls, two floor slabs, and a roof. Figure 4 shows the 3D-view of the demo project.

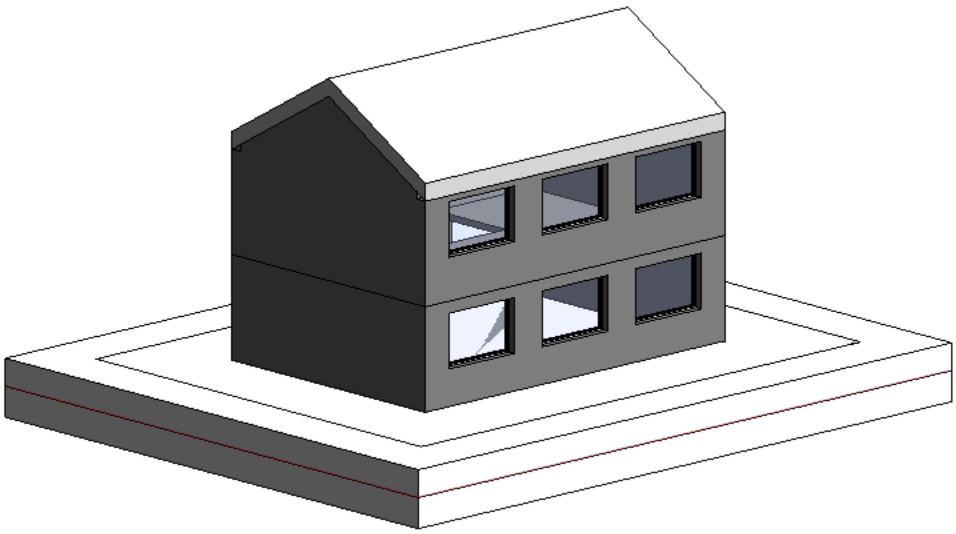


Figure 4: 3D-Building Model visualization from Revit

The following table gives an overview of the building objects parameters in the demo project.

No.	Assembly Description	Family and Type	Element ID	Instance Code	Or.	Lev.	Area m²
	Concrete - insitu						
	Floor: Foundation - 900mm (Cast-in-Place)						
1	Slab on Grade	Floor: Foundation - 900mm …	586351	(13)21.40,01.0		1	140
	Floor: Generic - 200mm (Interior) 2						
1	Floor Construction	Floor: Generic - 200mm (Interior)	595994	(23)23.06,02.2		2	96
	Basic Wall: Concrete - 400mm (Cast-in-Place)						
1	Exterior Walls	Basic Wall: Concrete - 400mm …	586063	(12)11.15,05.1.N2	N	1	19.2
2	Exterior Walls	Basic Wall: Concrete - 400mm …	645092	(12)11.15,05.1.N1	N	1	19.2
3	Exterior Walls	Basic Wall: Concrete - 400mm …	585968	(12)11.15,05.1.E	E	1	24.0
4	Exterior Walls	Basic Wall: Concrete - 400mm …	644734	(12)11.15,05.1.S2	S	1	19.2

No.	Assembly Description	Family and Type	Element ID	Instance Code	Or.	Lev.	Area m²
5	Exterior Walls	Basic Wall: Concrete - 400mm …	585914	(12)11.15,05.1.S1	S	1	19.2
6	Exterior Walls	Basic Wall: Concrete - 400mm …	640260	(12)11.15,05.1.W	W	1	24.0
7	Exterior Walls	Basic Wall: Concrete - 400mm …	642905	(12)11.15,05.2.N2	N	2	19.2
8	Exterior Walls	Basic Wall: Concrete - 400mm …	644964	(12)11.15,05.2.N1	N	2	19.2
9	Exterior Walls	Basic Wall: Concrete - 400mm …	641019	(12)11.15,05.2.E	E	2	24
10	Exterior Walls	Basic Wall: Concrete - 400mm …	640605	(12)11.15,05.2.S2	S	2	19.2
11	Exterior Walls	Basic Wall: Concrete - 400mm …	643638	(12)11.15,05.2.S1	S	2	19.2
12	Exterior Walls	Basic Wall: Concrete - 400mm …	640666	(12)11.15,05.2.W	W	2	24.0
13	Exterior Walls	Basic Wall: Concrete - 400mm …	641779	(12)11.15,05.3.E	E	3	11.2
14	Exterior Walls	Basic Wall: Concrete - 400mm …	636179	(12)11.15,05.3.W	W	3	11.2
	Roof						
	Basic Roof: Generic - 500 mm						
1	Roofing	Basic Roof: Generic - 500 mm	586094	(27)19.10,08.3		3	130

Table 1: Resource list of demo project building model

The goal is to link information about the schedule, the progress, and the required temporary construction items to the building object data received from Revit. Hence, a direct relation of TCIs requirements to each instance object in the building model is created, including all required data to passively monitor TCIs. As the building object is the central unit for all software applications, Revit will provide the main data source to build the knowledge graph which combines all data sources by linking them together. In order to make the data usable for the proposed solution, the model has to be parsed into structured data that describe the required model information. Therefore, different data has to be extracted from the Revit file that thoroughly describes the building objects. In terms of the prototyping, only wall objects are considered to fulfill the requirements of concept proofing.

This is being done with Dynamo scripts, directly in Revit, which automatically generate RDF triples from the available model data. The scripts are based on already existing solutions in GitHub (https://github.com/MadsHolten/OPM-REST/tree/master/tools/dynamo-scripts). The advantage of using visual scripting with Dynamo is that the data is directly converted in the right data format which can then be uploaded to an RDF triple store (RDF database) as Jena Fuseki. The following list is presenting all information that is extracted from Revit via the Dynamo scripts.

Revit Elements	Revit property	OWL property	OWL object	Datatype
Wall, Level	Revit GUID (UniqueId)	props:Revit_GUID	e.g. "450d31df-4383-4692-9be4-9c0935e083ef-0008f0ba"	xsd:string
Wall, Floor	Element ID	Props:Element_ID	e.g. "585914"	xsd:string
Wall, Floor	Inst. Element	rdf:label	e.g. "(12)11.15,05.1.S"	xsd:string
Wall, Floor	Inst. Element	rdf:type (a)	bot:Element	URI
Wall, Floor	Inst. Element	rdf:type (a)	product:Wall, product:Floor	URI
Wall, Floor	Inst. Element	rdf:type (a)	ont:Concrete400MmCastInPlace	URI
Wall, Floor	Type	rdf:label	e.g. "Basic Wall: Concrete - 400 mm (Cast-in-Place)"	xsd:string
Walls, Floors	Type	rdf:type (a) rdfs:SubclassOf	owl:Class; product:Wall	URI URI
Wall, Floor	Width Type Parameter	props:thickness	e.g. "0.4 m"	xsd:decimal
Wall, Floors	Material Type Parameter	props:material	e.g. "Concrete, Cast-in-Place, Grey"	xsd:string
Wall, Floor	Area Inst. Parameter	props:area	e.g. "27.0 m²"	xsd:decimal
Wall	Length Inst. Parameter	props:length	e.g. "8.4 m"	xsd:decimal
Wall	Height Inst. Parameter	props:height	e.g. "3.0 m"	xsd:decimal
Level	Inst. Element	rdf:type (a)	bot:Storey	URI
Level	Inst. Element	rdf:label	e.g. "Level 1"	xsd:string
Level	Base Constraint Level	bot:hasElement	inst:wall; inst:floor	xsd:string
Wall, Floor	Surrounding Element	bot:adjacentElement	inst:wall	URI
Wall	Wall Orientation	props:angle	e.g. "90.0"	xsd:decimal

Table 2: Properties exported from Revit

With the generated Revit data graph, all required information from the building model is exported and ready to create relations with the other data graphs, specified earlier.

The first approach with Dynamo aimed to create RDF triple files for each property that needs to be exported from Revit. By doing this, the model data was saved as turtle files (.ttl) and then uploaded into the RDF triples store in Jena Fuseki. Figure 5 shows the Jena Fuseki interface to upload the generated turtle files into the triple store.

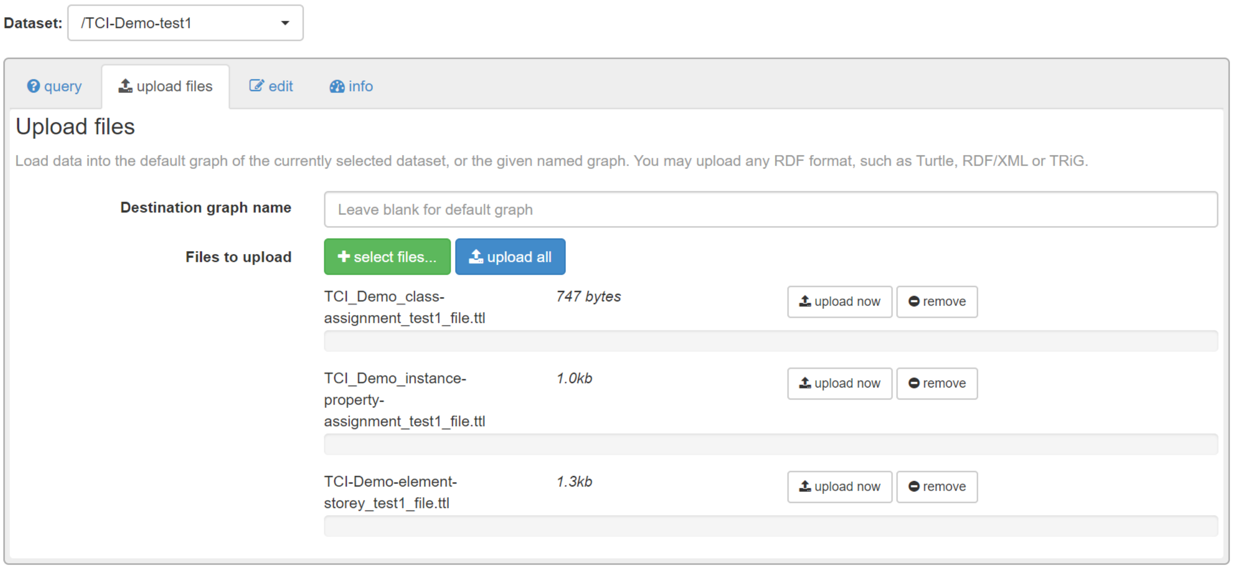


Figure 5: Manual approach of uploading the required data files into the triple store

The fact that this approach required a manual upload of all property data files into the triple store makes it very time-consuming and limits the automation factor. In order to increase automation, the next approach aimed to directly write the triples into the triple store. Therefore, the existing scripts are extended with a Python code which enables to update a data set in the triple store with the extracted model data. By sending an HTTP POST request to the Fuseki database, the generated triples can be written into the specified dataset by specifying its URL. In Fuseki, there are two options for inserting data to an existing dataset. http://localhost:3030/TCI-Demo-Revit-data/data is the URL where data is stored as an RDF-graph. It can be also be used as the URL for the HTTP POST request as the Fuseki database allows to directly write to the storage location. Another, slightly more difficult approach is to write the HTTP POST request to http://localhost:3030/TCI-Demo-Revit-data/update. In theory, this will update the dataset with new data, but in practice, it has the same result as the other method. The only difference is that with the second approach, the triples are written with their namespaces as prefixes are not published.

Figure 6 shows the resulting data graph that combines the different turtle files in the triple store, based on their relation.

```
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" .

wallinst:450d31df-4383-4692-9be4-9c0935e083ef-0008f0f0
        a                    product:Wall , ont:Concrete400MmCastInPlace ;
        rdf:label            "(12)11.15,05.1.E" ;
        bot:adjacentElement  wallinst:450d31df-4383-4692-9be4-9c0935e083ef-0008f14f , wallinst:c1037085-1aff-4644-8770-66dc41edbf0b-0009d67e ;
        props:Element_ID     "585968" ;
        props:Revit_GUID     "450d31df-4383-4692-9be4-9c0935e083ef-0008f0f0" ;
        props:angle          90.0 ;
        props:area           24.0 ;
        props:height         3.0 ;
        props:length         8.4 ;
        props:level_simple   "Level1" .

wallinst:450d31df-4383-4692-9be4-9c0935e083ef-0008f14f
        a                    product:Wall , ont:Concrete400MmCastInPlace ;
        rdf:label            "(12)11.15,05.1.N2" ;
        bot:adjacentElement  wallinst:c1037085-1aff-4644-8770-66dc41edbf0b-0009d7e4 , wallinst:450d31df-4383-4692-9be4-9c0935e083ef-0008f0f0 ;
        props:Element_ID     "586063" ;
        props:Revit_GUID     "450d31df-4383-4692-9be4-9c0935e083ef-0008f14f" ;
        props:angle          180.0 ;
        props:area           19.2 ;
        props:height         3.0 ;
        props:length         6.2 ;
        props:level_simple   "Level1" .
```

Figure 6: Excerpt of the resulting Revit data graph showing wall instances

The dataset of the 3D-Model is built on existing ontologies, especially from the Linked Building Data community group, describing the context of a building in Linked Data format. Thus, there was no need to develop a new ontology for this dataset. The entire Revit data graph and all following data graphs of this demo project can be found in the GitHub repository LBD-for-TCI (https://github.com/Alex-Schlachter27/LBD-for-TCI/tree/master).

2.3 LBS Data

Schedule information is 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, which represent construction activities that include information about 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 time information with the location dimension. Besides many proven advantages, this scheduling approach allows a continuous and efficient construction process by reducing waste.

In this demo project, the LBS-approach is utilized with the help of VICO Office, a scheduling software that enables a BIM-integrated and location-based scheduling process (figure 7). The advantage of location-based scheduling is that the location dimension provides a new level of detail that enables to sequence the construction progress based on both the sequence logic of construction and the logic of location to avoid interferences and waste. For the passive planning of formwork, this approach furthermore allows quantifying the amount and types of formwork which is required for the individual tasks. Each task is based on a schedule sequence and its specific location and therefore, the construction management would know exactly when and where which kind and amount of formwork is needed on site.

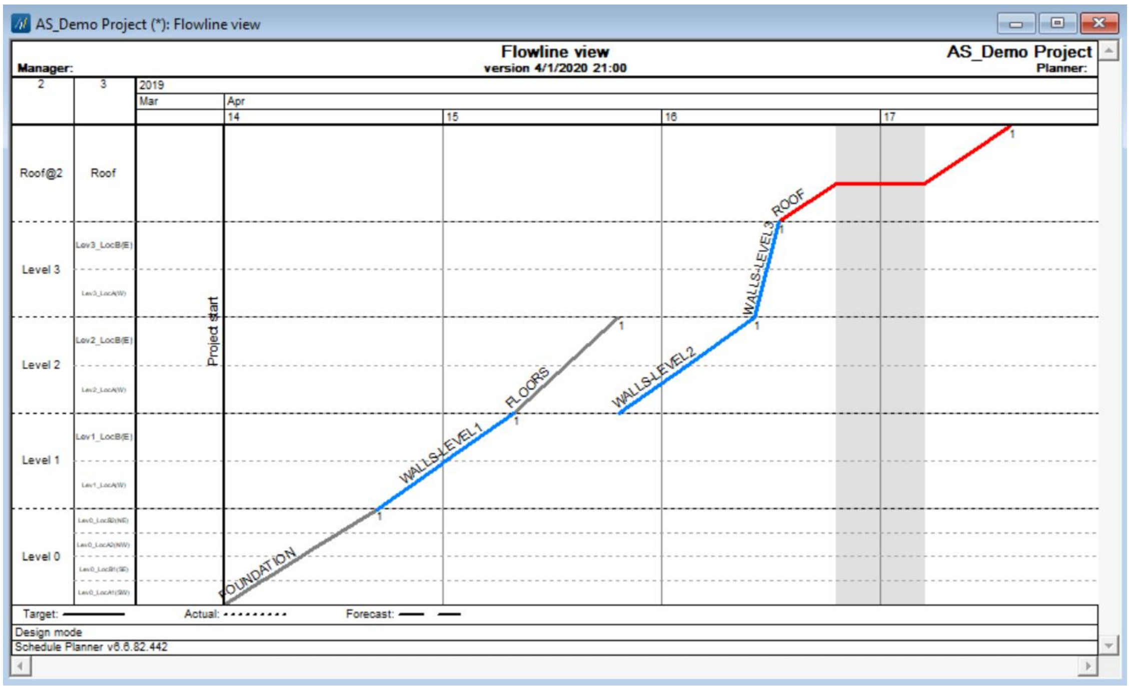


Figure 7: Location-based schedule of the demo project

After establishing the schedule with tasks that are linked to each of the available building objects and their location in the model, all available data has to be extracted in order to explore the data for the valuable instances. In this case, VICO provides the data in five different datasets (Cost Plan, LBS, Scheduling System, Takeoff System, and CAD Model System) as JSON files that are interconnected with common ID codes. Currently, Exigo is exporting only three (Cost Plan, LBS, Scheduling System) of the five available datasets for the use of the progress monitoring application Exicute. The issue is explained in the following table, that presents the required data from VICO, how it can be translated into RDF, and in which dataset it can be found.

VICO property	VICO dataset	OWL property	Datatype
Element ID	CAD Model System	props:Element_ID	xsd:string
compLoid	All systems	tci:hasCompLoid	xsd:string
locLoid	LBS	tci:haslocLoid	xsd:string
Location Name	LBS	tci:hasLocation	xsd:string
schedloid	Scheduling System	tci:hasschedLoid	xsd:string
taskloid	Scheduling System	tci:hastaskLoid	xsd:string
taskPlannedStartDate	Scheduling System	tci:taskPlannedStartDate	xsd:DateTime
taskPlannedEndDate	Scheduling System	tci:taskPlannedEndDate	xsd:DateTime
taskActualStartDate	Scheduling System	tci:taskActualStartDate	xsd:DateTime
taskActualEndDate	Scheduling System	tci:taskActualEndDate	xsd:DateTime
taskProgressDate	Scheduling System	tci:taskProgressDate	xsd:DateTime
taskProgressCompletion	Scheduling System	tci:taskProgressCompletion	Xsd:nonNegativeInteger

Table 3: Required data from VICO and where it is located

Going through the raw data of VICO, it was recognized that all required data regarding the schedule and location is already available through the export of Exigo with the extraction tool ExiLink. However, in order to create a relation between the VICO data and the 3D-Model data, some reference code is needed in order to map the two datasets. In this case, the reference code would be the Element ID, which is created in Revit for every single building object and gets transferred to the CAD Model System dataset in VICO. Besides the CAD Model System, the Takeoff System also needs to be exported in order to link the Element ID to the schedule and location data, because the relation goes through the component ID (compLoid). This, however, is not currently utilized from Exigo and would require processing much more data as it is currently processed. Hence, a solution is needed that exports all of the required data.

In this case, two options are available to solve the problem. The first is to modify the program that was coded from Exigo to extract the VICO data into a SQL format, to also support the two missing datasets. The other option is to write a program that is receiving the required JSON files, selects the data that is needed as specified in table 3 and writes it directly in RDF language to a chosen dataset in a triple store.

For the demo-project, a manual extraction of the data was chosen to simplify the process and get a quick result. For the further development of the solution and the later use of the process, however, a program needs to take care of the data extraction of the VICO data. Either to use the SQL data from the existing VICO-extraction from Exigo with the extraction tool ExiLink or to develop an own program which is able to convert the raw JSON data into RDF triples and write it to a defined triple store.

In order to store the data in Linked Data terminology, first, there is a need to develop a new ontology that describes the data from VICO (see OWL property column in table 3) and is able to create a link to the other datasets through property relations. This LBS ontology was built with an open-source tool called "Protégé" and has the following fictive namespace: http://test/lbs/. The next step in processing the data into RDF format is to map the existing VICO data within the developed ontology classes, instances, and properties. The resulting data graph for the LBS data is shown below.

```
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" .

inst:1000.0.145920  a                  lbs:CompLoid , product:Wall ;
        lbs:hasCompLoid                "1000.0.145920" ;
        lbs:hasLocation                "Lev1_locb(e)" ;
        lbs:haslocLoid                 "1000.0.355015" ;
        lbs:hasschedLoid               "1000.0.321768" ;
        lbs:hastaskLoid                "1000.0.358593" ;
        lbs:taskActualEndDate          "NULL"^^xsd:dateTime ;
        lbs:taskActualStartDate        "NULL"^^xsd:dateTime ;
        lbs:taskPlannedEndDate         "2019-04-09 11:57:36.000"^^xsd:dateTime ;
        lbs:taskPlannedStartDate       "2019-04-08 07:28:48.000"^^xsd:dateTime ;
        lbs:taskProgressCompletion     "0.0"^^xsd:nonNegativeInteger ;
        lbs:taskProgressDate           "NULL"^^xsd:dateTime ;
        props:Element_ID               "585968" ;
        props:Revit_GUID               "450d31df-4383-4692-9be4-9c0935e083ef-0008f0f0" .
```

Figure 8: Excerpt of the resulting LBS data graph showing wall instances

2.4 Progress Monitoring Data

As seen in figure 8, some of the objects of each wall instance are returning "NULL" as their value, meaning that their value has not yet been specified. This information is classified as progress data because it provides information about the current progress of the construction activities and is an optional feature of the VICO schedule planner to monitor the construction activities based on the planned schedule. In Exigo, a cloud platform was developed to generate this information from the construction site and write it back to the schedule.

The platform is called Exicute and includes an application that allows the contractors on a construction site to document their progress within a mobile app. The cloud platform then receives the information and updates the VICO data with information as "Progress Date", specifying the date when the progress is documented, "Progress Completion" in % and per task as well as the "Actual Start Date" and Actual End Date" of each construction task. Figure 8 visualizes the data system and the workflow of the Exicute platform.

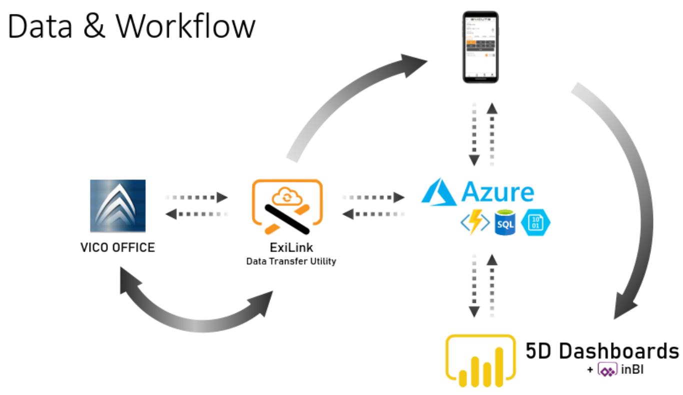


Figure 9: Data system and workflow of Exicute

For the purpose of the proposed solution in this thesis, the already existing progress monitoring of Exicute can be utilized to establish passive monitoring of TCIs, based on the progress of the permanent building parts as there will be a direct relation between each building element and the temporary construction items, required to construct the element. Hence, the TCI utilization plan with its information about when and where, which type and quantity of TCIs are needed on site, gets updated with every progress update from the construction site. This passive monitoring of TCIs already significantly improves the management of these items. However, further development might include IoT-tracking sensors on TCIs to not only receive the information where the items are supposed to be but also create the ability to verify their actual location. This idea is further explained in chapter 6.3 of this thesis.

In conclusion, the progress monitoring data can be seen as a data extension of the LBS data and thus, will be managed within the LBS dataset.

2.5 TCI-Data

This dataset comprises the main knowledge graph of the TCI-Demo-project as it represents the Temporary Construction Items in a newly established TCI Ontology (http://test/tci/). The individuals of the ontology are forming the default set of formwork, which is used to calculate the TCI-utilization plan before the supplier and specific TCI-products are known. The default formwork set is developed with consideration of existing formwork solutions. The following figure is presenting the default formwork set with their specific dimensions.

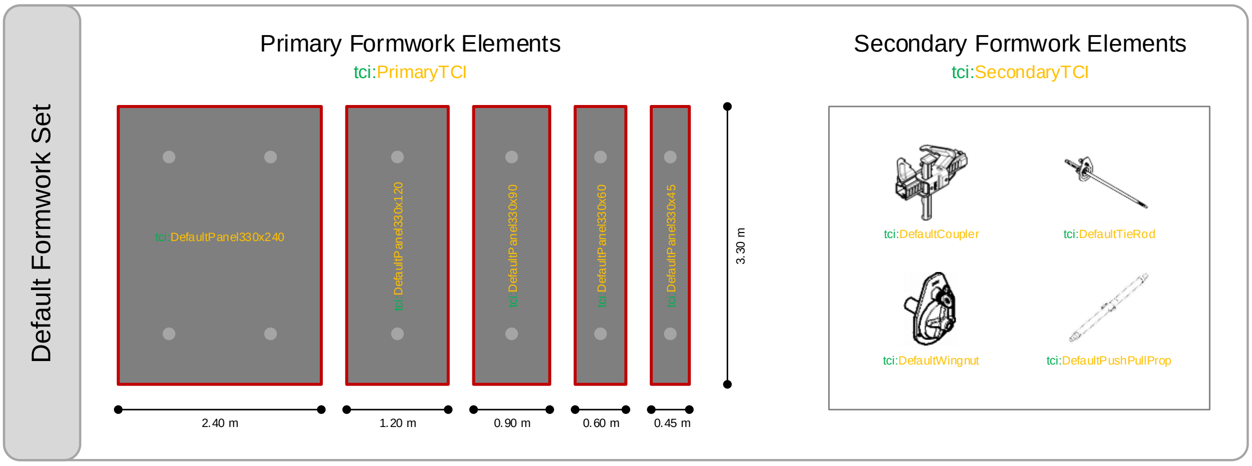


Figure 10: Default Formwork Set

Based on the individual standard dimensions, the quantities of TCIs can then be calculated for a specific wall layout. For simplification reasons, a premise is defined for the creation of building models. This premise requires that the BIM model and schedule are aligned with the construction process. This means that each building element can be assigned to one unique construction task, consisting of schedule and location information, in order to avoid splitting up building elements when creating the location-based schedule. The length of a wall, for example, represents the section of a wall that is constructed in one sequence with a closed set of formwork (a formwork cycle). Hence, the formwork quantity is calculated for each wall section and according to the sequence of construction. In this regard, construction benefits from location-based scheduling as it allows to schedule a sequence of tasks based on their location and following a specific logic. Having the parameters of a wall as length and height consequently enables to quantify the required forms with standard dimensions. Thus, the stated premise ensures the correct deduction of formwork quantities.

Next to the default formwork set, which already gives precise information about what quantities of TCIs are required over time in the construction project, the solution must allow to include specific product catalogues as soon as a supplier and their specific solution is selected for a construction site. By including the actual products which are used on site, the TCI utilization plan directly represents what is going on and what should happen on site and hence, 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, the formwork was only calculated with the default set, as it already serves as a proof of concept. Yet, an additional ontology was developed for an example product for the further development of the solution. The chosen example product catalogue is based on the formwork solution "MAXIMO MX15" from the formwork and scaffolding supplier PERI. The complete product catalogue, provided from PERI, can be found with the following URL: https://www.peri.com/brochures/jcr:af4fc9a6-1bca-40ef-ba82-849c803bd562/MAXIMO-Panel-Formwork.pdf. As with the default formwork set, an ontology was created with the information from the provided product catalogue, having the following fictive namespace: http://test/peri/. In this case, the ontology was created manually to represent the product catalogue in RDF language. In the future development of the proposed solution, ontologies of specific product catalogues should be created by the supplier itself which can then be accessed through an open URL. A business case for suppliers could be established that would create incentives to publish their products as RDF data graphs. An example where this future scenario is already put in practice is the BAUKOM /catalogue, where precast building elements are listed in a data model of RDF ontologies (Costa & Pauwels, 2015). In order to differentiate the TCI utilization plan regarding its status, if a specific product catalogue is available, a property status needs to be included in the TCI data. Before a supplier is chosen and a specific product can be selected, the default formwork is classified as *opm:Assumed*. In contrast, specific products will be classified as *opm:Confirmed*. The algorithm that calculates the formwork quantities shall, therefore, look for the property status if a confirmed product is available and if this condition is true, the confirmed product catalogue shall be preferred over the default set of formwork. In this way, it is assured that the TCI utilization plan always considers the level of detail regarding TCIs that are currently available in the construction project.

Chapter 3. Data Management

As presented in the export of the Revit data, the RDF triple store "Apache Jena Fuseki" is utilized to store all the triple relations as data graphs. Fuseki is a SPARQL server, that is able to store RDF data and allows to query the data over HTTP, based on SPARQL 1.1 protocols for query and update. The storage system also provides security by using an authentification system and is accessible through the URL http://localhost:3030/. In general, a triple store is a database to store and query RDF triples. These triples can be stored within the repositories of the triple store. Repositories are databases within an RDF triple store that must have one default data graph and zero or more named graphs.

The data in a triple store is can be processed directly in the interface of Fuseki, using a SPARQL query. 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. Figure 11 shows a simple configuration of this advanced data processing.

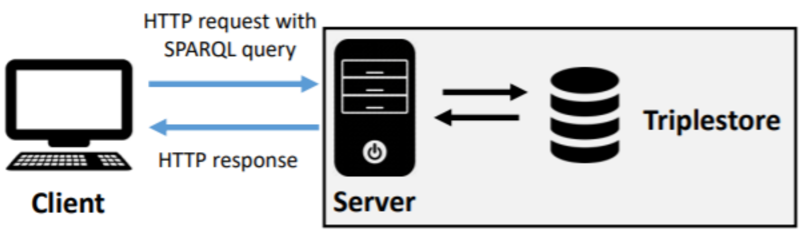


Figure 11: SPARQL query over HTTP request with Triple Store

First of all, the data which is extracted from different software applications of the construction industry is stored in separate datasets. On the one hand, it is simple to write data to an individual dataset as its URL is accessible. On the other hand, having the data in individual datasets allows to receive the data with a simple HTTP request, containing a SELECT query. Due to this flexibility in data management, the data is first stored in individual datasets in the Fuseki triple store.

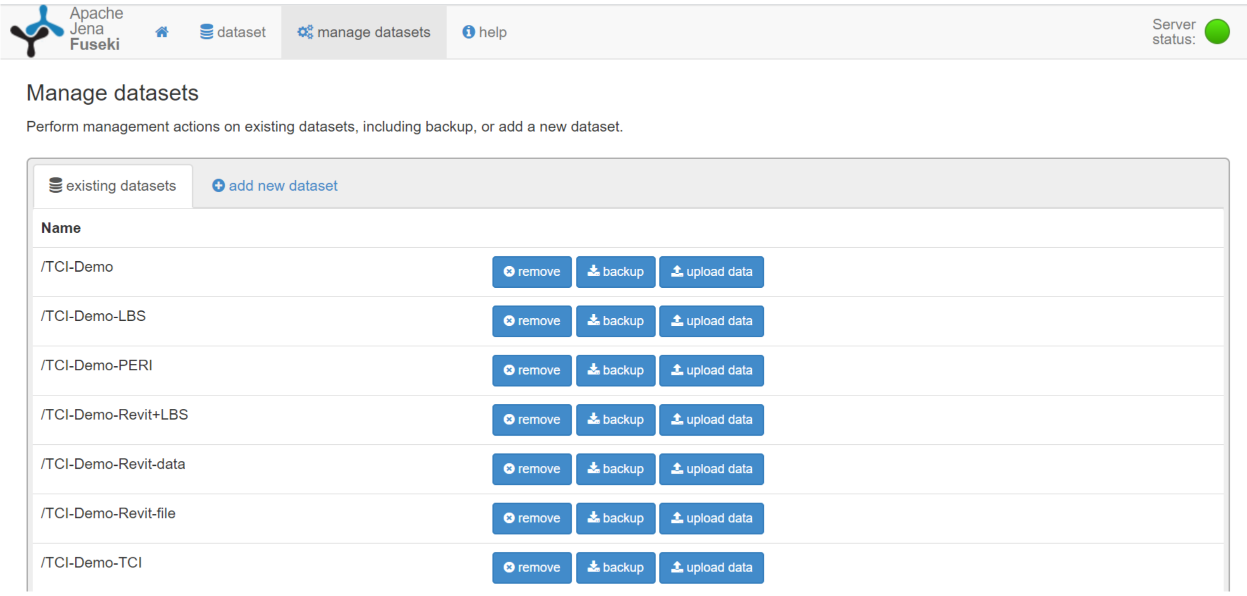


Figure 12: Fuseki Triple Store - Created datasets

The raw data from the previous chapter is stored in the individual datasets with the endings /TCI-Demo-Revit-data, /TCI-Demo-LBS, /TCI-Demo-TCI and /TCI-Demo-PERI (figure 12).

The data graph /TCI-Demo-PERI is containing a specific product catalogue of the formwork solution PERI MAXIMO MX15 and is not used in this Demo Project. The /TCI-Demo dataset is kept empty as this will be used as the combined data graph where the individual datasets are put into named graphs and then are queried together into a combined data graph. Furthermore, the results of the automatic formwork planning also need to be stored in the combined data graph in order to be able to derive the TCI utilization plan from that graph. The use of named graphs allows to query data from all named graphs in one dataset and thus, combining the information. Therefore, the individual data graphs must be stored into one common dataset. This can be done by directly storing the data into named graphs or combining them subsequently with a federated query. In this demo project, however, the data graphs are copied manually to individual named graphs of the dataset /TCI-Demo and are then added into a combined data graph by querying each named graph. How this has been done in detail is explained in the following chapter. The following two queries show how to copy named graphs in order to combine the data.

```
ADD <http://localhost:3030/TCI-Demo/data/Revit> TO GRAPH <http://localhost:3030
/TCI-Demo/data/RevitLBS> ;
ADD DEFAULT TO GRAPH http://localhost:3030/TCI-Demo/data/Combined ;
```

Figure 13: Queries to Add named graphs to another graph

Chapter 4. Data Processing & Querying

In the last step, all data was stored in individual graphs in the fuseki triple store http://localhost:3030/. By that, the required raw data is ready to get processed to develop a TCI utilization plan.

The relation between the LBS and Revit data is already created with the common property "Element ID". With a simple owl:sameAs relation, all wall instances from both data graphs can be mapped in order to have both the building element and time information. Thus, the main challenge of this chapter is the creation of a rule-based algorithm that calculates the TCI requirements for each building element and hence, links the Revit data with the TCI data.

In this demo project, the automatic planning of TCIs with a rule-based algorithm is simplified and serves as a proof of concept for the further development of the solution. The following list defines all simplifications:

a) Formwork is chosen to represent all TCIs that can be linked to a model object

b) One dimensional calculation of vertical formwork for the construction of concrete walls

c) Height of forms is always greater than the wall height, hence no need for consideration of heights

d) Utilization of only a default set of forms with specific parameters

e) Assumption that walls in the building model are modeled as they are constructed, meaning that the wall separation in the model represent the sequencing of the construction activity which has to be covered by formwork

f) Corner Panels are not considered in the demo project

g) Formwork is calculated for the entire length of each modeled wall

The specified simplifications in the demo project enable to focus on the essential aspect of prototyping a solution without restricting the developed solution to be extended again later to cover the whole context. In this case, the created algorithm must possess a certain flexibility to be modified and adjusted. Ceiling formwork, for example, can be considered by adding a dimension to the calculation and the Revit data can already specify corners to also consider corner panels in the demo project.

Other TCIs as scaffolding or fencing might be considered as well by creating a simple calculation and a link to an existing model object. Thus, the chosen simplifications ease the development of a proof of concept but don't add any insurmountable obstacles to the solution development. Furthermore, the simplified demo project still requires some effort to work and is seen as a valid project for the purpose of prototyping.

The problem of placing vertical standard forms on a given wall geometry mainly depends on the length and height of the wall. Given that the height of the walls (h = 3.00 m) of the demo building model is at all times shorter than the height of the default standard forms (h = 3.30 m), the only parameter that impacts the quantities of forms and formwork layout is the length. Based on the given standard lengths of the formwork elements as well as the given length of the walls, an algorithm can calculate the formwork layout with the least amount of forms used. The following rules shall be applied in the algorithm:

- Formwork is calculated for each wall instance in the given Revit dataset
- For the given wall length, the least amount of standard forms shall be calculated
- The default formwork set is based on the standard formwork MAXIMO MX15 and consists of the following primary TCIs: DefaultPanel330x240, DefaultPanel330x120, DefaultPanel330x90, DefaultPanel330x60, DefaultPanel330x45
- If the default formwork layout cannot cover the entire wall, the empty space will be filled with filling material (TimberFilling) which is specified by its length
- Secondary TCIs as couplers and wingnuts are items that are supporting the primary TCIs and are quantified based on rules from existing formwork solutions and the calculated quantity of standard forms
- The following secondary TCIs are used in the demo project: DefaultCoupler, DefaultPushPullProp, DefaultTieRod, DefaultWaler, DefaultWingnut

The intended formwork calculation for an example wall as specified in the ruleset is visualized for a better understanding in the following figure. It shows the required information from both datasets (Revit and TCI) and how the algorithm shall calculate the formwork utilization in order to use the least amount of forms and be able to cover the whole wall length with formwork.

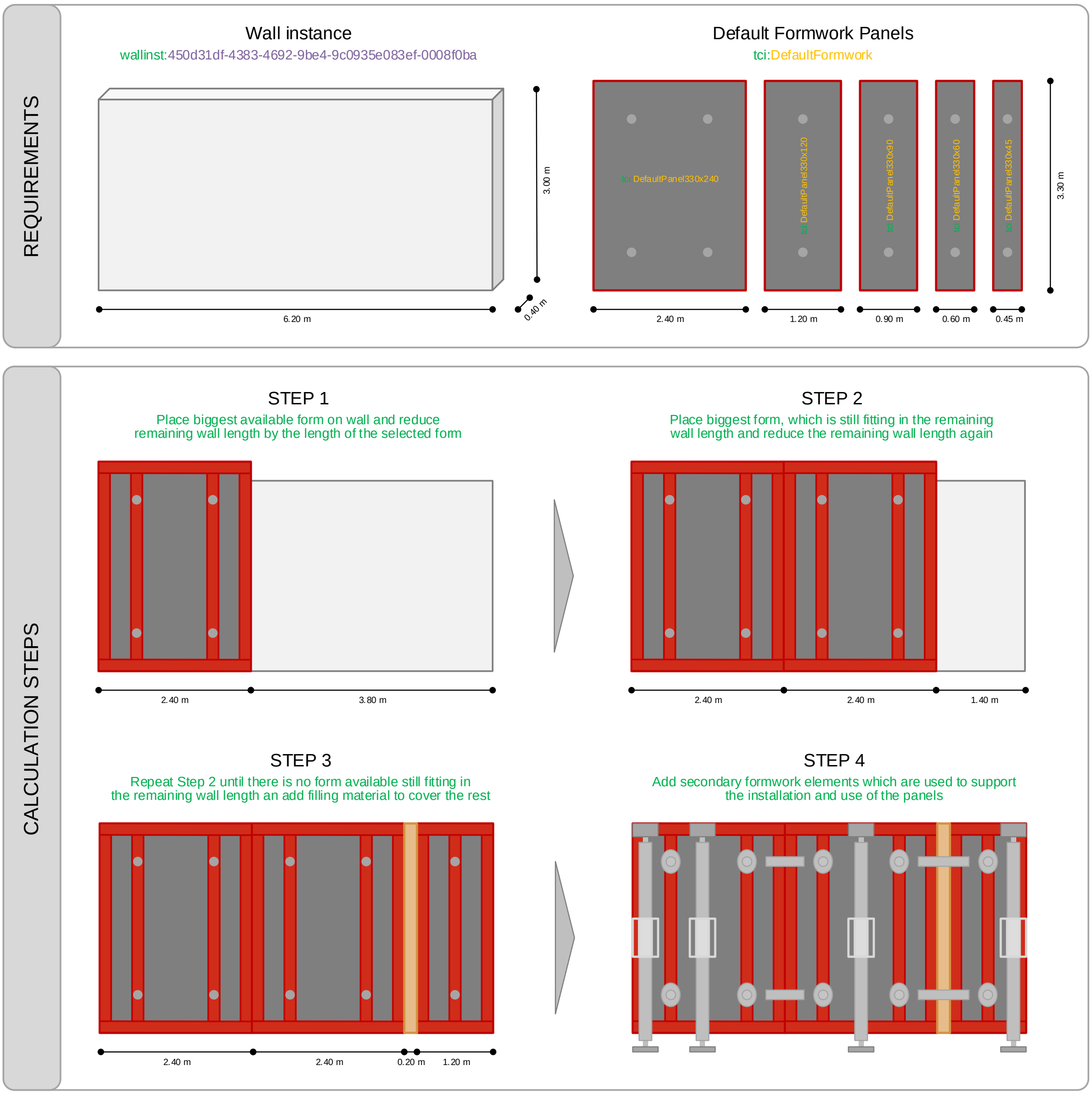
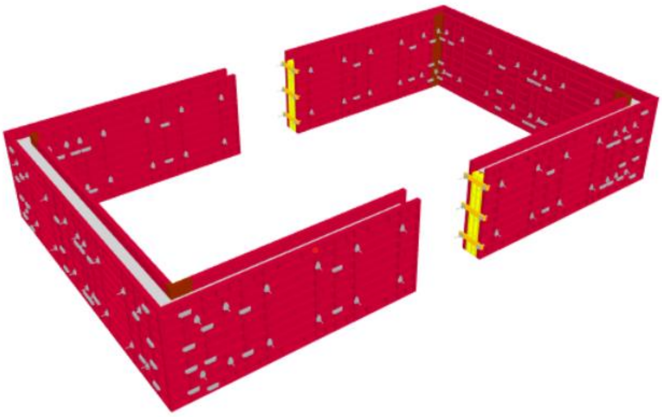


Figure 14: Formwork Calculation Visualization

Integrating these rules into a single calculation required a certain flexibility and calculation power using different datasets. Initially, it was planned to run a SPARQL query directly against the developed datasets in the triple store. However, due to the limited flexibility of such a query, it was decided to write a small program that accesses the data from the triple store via a SPARQL query over an HTTP request to the SPARQL endpoint. After receiving the required data from the triple store, the program calculates the required TCIs for each instance building element and writes the data back to the Fuseki triple store.

As existing code blocks in Javascript (**fuseki.js**) are used to get the data from the triple store with an HTTP-request, Javascript was chosen as the programming language to develop the small program. However, other programming languages as Python are able to do the same. The developed program is named **index.js** and can be found in the GitHub repository LBD-for-TCI under Demo Project (https://github.com/Alex-Schlachter27/LBD-for-TCI/tree/master).

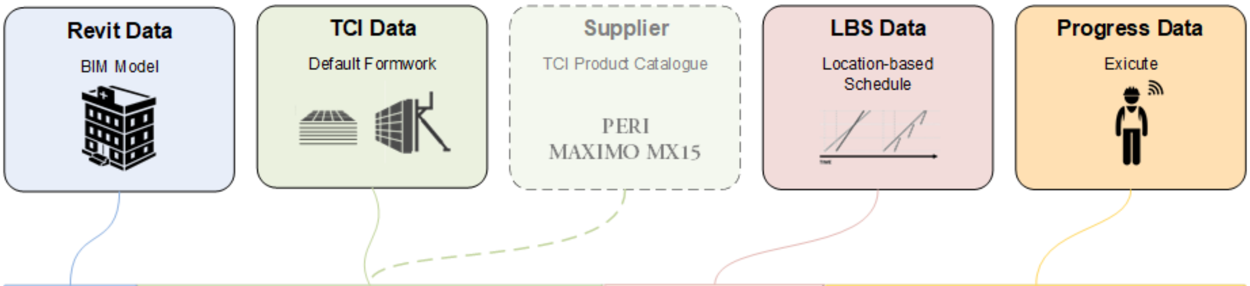
To provide some guidance for the development of the calculating functions in the program, an automatic formwork planning software from PERI (https://quicksolve.peri.app/) is explored. In this application, quantities of formwork from a selected product catalogue (in this case MAXIMO MX15) are calculated by specifying the geometry and sequencing of a wall structure. Figure 15 shows an example formwork sequence and the respective part list consisting of primary TCIs as the standard panels and secondary TCIs.



		1	2	Maximum Pcs.	Correction Pcs.	Sum Pcs.	Weight kg
	ALIGNMENT COUPLER BFD Art.-No. 023500 4.58 kg	12	16	16	0	16	73.28 kg
	WALER 85 Art.-No. 023551 8.52 kg	6	6	6	0	6	51.12 kg
	TRIO BULKHEAD TIE TS, GALV. Art.-No. 023640 1.14 kg	12	12	12	0	12	13.68 kg
	WINGNUT PIVOT PLATE DW15 GALV Art.-No. 030370 1.66 kg	12	12	12	0	12	19.92 kg
	MAXIMO-PANEL MX 270X240 -/- Art.-No. 112006 336.00 kg	4	6	6	0	6	2016.00 kg
	MAXIMO-PANEL MX 270X120 Art.-No. 112022 186.00 kg	2	2	2	0	2	372.00 kg
	MAXIMO-PANEL MX 270X 45 Art.-No. 112078 77.50 kg	2	-	2	0	2	155.00 kg
	WINGNUT MX15 Art.-No. 112386 2.58 kg	12	16	16	0	16	41.28 kg
	TIE MX15 30-40 Art.-No. 112464 4.43 kg	12	16	16	0	16	70.88 kg
	MAXIMO-PANEL MX 270X 30 Art.-No. 112090 61.80 kg	-	2	2	0	2	123.60 kg
	Plywood Width: 40,0 cm, Height: 240,0 cm, Depth: 2,1 cm	2	2	2	0	2	
	Filler timber Width: 8,0 cm, Height: 240,0 cm, Depth: 10,4 cm	6	-	6	0	6	

Figure 15: Wall covered in formwork and the respective part list from PERI Quicksolve

Two reports of example projects in PERI Quicksolve are included in the thesis as appendix 7, helping to develop the prototype solution. By analyzing and exploring the calculating algorithm of the existing solution from PERI, information was gathered to develop the calculation in the prototyping program. In addition to using PERI Quicksolve as a supporting tool to develop the program, a solution-based approach was selected in which the desired solution is first outlined to identify all required data. This approach provides a starting point for a structured development of the program script as the program can be coded step by step to return the desired output. The first step is to define the raw data from different data graphs that are needed for the calculation (figure 16).



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 16: Linked Data Query Output Table for TCI Utilization Plan, Example

Then, for each data graph, an individual SPARQL query must select the required data and map it into a JSON format in order to work with it in Javascript. Afterwards, the algorithm has to calculate the required quantities of formwork for each wall instance and push the selected TCI elements to the respective wall object. The following figure reveals the output JSON object for a wall example with the calculated TCIs. The result of the calculation contains enough information to create a formwork utilization plan for a construction project.

```
{"wallinst": "http://test/walls/450d31df-4383-4692-9be4-9c0935e083ef-0008f0ba",
   "length": 6.2,
   "TCIsIn": [
          {"TCIinst": "http://test/tci/DefaultPanel330x240_0", "length": 2.4},
          {"TCIinst": "http://test/tci/DefaultPanel330x240_1", "length": 2.4},
          {"TCIinst": "http://test/tci/DefaultPanel330x120_0","length": 1.2}],
   "TCIsOut": [
          {"TCIinst": "http://test/tci/DefaultPanel330x240_0", "length": 2.4},
          {"TCIinst": "http://test/tci/DefaultPanel330x240_1", "length": 2.4},
          {"TCIinst": "http://test/tci/DefaultPanel330x120_0","length": 1.2}],
   "secTCIs": [
          {"TCIinst": "http://test/tci/DefaultCoupler", "weight": 4.58},
          {"TCIinst": "http://test/tci/DefaultTieRod", "weight": 4.43},
          {"TCIinst": "http://test/tci/DefaultWingnut", "weight": 2.58},
          {"TCIinst": "http://test/tci/DefaultPushPullProp", "weight": 22.8}],

   "TCIsCount": [
          {"TCIinst": "http://test/tci/DefaultPanel330x240", "Count": 4},
          {"TCIinst": "http://test/tci/DefaultPanel330x120", "Count": 2},
          {"TCIinst": "http://test/tci/TimberFilling", "Count": 2},
          {"TCIinst": "http://test/tci/DefaultCoupler", "Count": 4},
          {"TCIinst": "http://test/tci/DefaultTieRod", "Count": 8},
          {"TCIinst": "http://test/tci/DefaultWingnut", "Count": 8},
          {"TCIinst": "http://test/tci/DefaultPushPullProp", "Count": 8}],
   "TimberFilling": [
          {"TCIinst": "http://test/tci/TimberFilling", "Length": 0.2},
          {"TCIinst": "http://test/tci/TimberFilling", "Length": 0.2}]},
```

Figure 17: Output JSON Object of the developed program

In the output data, the object TCIsIn and TCIsOut represent the formwork instances for each side of the wall which are then enumerated with a running integer to be able to later address the individual form. This helps, for example, when including IoT-tracking of forms as one could trace each form back to which location and construction activity it belongs. In this case, the TCIs inside and outside of the wall are the same, as the wall is regarded as an individual object. The results of the program were then compared to the results from PERI Quicksolve for a similar wall design and thus, validated with a professional software solution. Both the professional calculation from PERI and the proposed prototype solution conclude in a realistic formwork layout for the given wall structure. However, the developed program in this stage of prototyping shows the following limitations compared to the professional formwork calculation.

- Corner elements need to be considered in the calculation by detecting if a wall has a corner ending. The wall-length has to be reduced respectively with the length of the corner elements if a corner is detected.
- If a wall has no corner, the ending must be closed with walers and plywood at the end of a wall sequence to prevent the concrete from pouring out. This has not been considered in the demo project.
- The plywood has the height of the formwork, the width of the concrete thickness, and an approximate thickness of 2 cm.
- Three walers shall be placed around the open wall ending to support the plywood and hold the concrete in place.

The listed shortcomings will be included in the further developing process of the program for the followed case study.

The final part of the program must write the data back into the triple store in order to create a combined graph which contains the data of all datasets as well as the calculated output data of the program. As described in the previous chapter, the data graphs are stored in individual named graphs within the dataset http://localhost:3030/TCI-Demo/ where the default graph is empty. The program is able to write the data to the default graph by creating an INSERT query that writes to the URL http://localhost:3030/TCI-Demo/update. As soon as the data is transmitted to the default graph, a new graph (http://localhost:3030/TCI-Demo/data/Combined) can be created by querying each named graph and adding them to the newly created combined data graph. The final dataset layout in Fuseki is shown below:

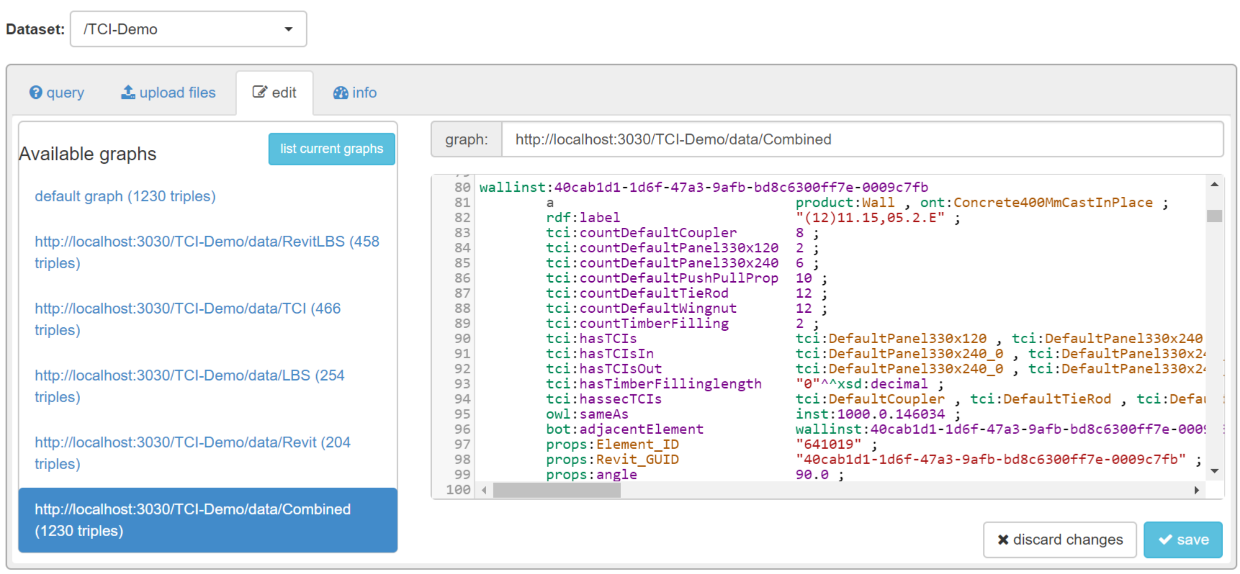


Figure 18: Final TCI-Demo dataset layout with named graphs

The created named graph is now containing a total of 1230 triples and has all the information to create the desired output table from figure 16. The combined data graph contains the individual datasets Revit, LBS, and TCI. It combines the building model elements with information about the schedule, the current progress as well as detailed information as quantities of TCIs that support the construction activities. By querying the data graph with a SPARQL-query, specific data can be obtained in a table format, ready for a data export in a convenient format. Using the following SPARQL-query against the combined data graph enables to narrow down the huge amount of data to the essential and desired outcome.

```
SELECT ?Element_ID ?length ?PrimaryTCIs ?TCIsCount ?SecondaryTCIs ?2TCIsCount
?Location ?PlannedStartDate ?PlannedEndDate ?ActualStartDate ?ActualEndDate ?P
rogressDate ?ProgressCompletion

WHERE {GRAPH <http://localhost:3030/TCI-Demo/data/Combined>
{
?Revitinst a product:Wall ;
    props:Element_ID ?Element_ID ;
    props:length ?length ;
    tci:hasTCIs ?PrimaryTCIs;
    tci:hassecTCIs ?SecondaryTCIs .

?1Countprop tci:iscounting ?PrimaryTCIs .
?Revitinst ?1Countprop ?TCIsCount .
?2Countprop tci:iscounting ?SecondaryTCIs .
?Revitinst ?2Countprop ?2TCIsCount .

  ?VICOinst a lbs:CompLoid ;
    props:Element_ID ?Element_ID ;
    lbs:hasLocation ?Location;
    lbs:taskPlannedStartDate ?PlannedStartDate;
    lbs:taskPlannedEndDate ?PlannedEndDate;
    lbs:taskActualStartDate ?ActualStartDate;
    lbs:taskActualEndDate ?ActualEndDate;
    lbs:taskProgressDate ?ProgressDate ;
    lbs:taskProgressCompletion ?ProgressCompletion .

FILTER (?VICOinst != ?Revitinst)
}}
```

Figure 19: SPARQL-Query against combined graph

The shown query was developed to create a narrowed down dataset in order to derive a TCI utilization plan. It shall provide a similar output as the desired output table in figure 16. First, the query is specifying the main subject, which in this case are the wall instances, from both the Revit and the VICO source. As the program **indexSameAs.js** was mapping the wall instances from both sources with the owl:sameAs relationship by the common Element ID, all information from both data sources can be queried and linked to each wall instance. The result of the simple query in figure 19 is then displayed in table format (CSV-file) and can be further utilized e.g. for data visualization. This output table is representing the main result of the demo project and serves as a proof of concept of the proposed solution as it contains each wall instance and information about when and where which types and number of TCIs are needed on site. An excerpt from the output table is can be found in table 4.

Revit		TCI					VICO		Exicute			
Element _ID	length	PrimaryTCIs	TCIs Count	SecondaryTCIs	2TCIs Count	Location	PlannedStartDate	PlannedEndDate	Actual StartDate	Actual EndDate	Progress Date	%
"645092"	"6.2"	"tci:DefaultPanel330x120" "tci:DefaultPanel330x240" "tci:TimberFilling"	"2" "4" "0.2"	"tci:DefaultCoupler" "tci:DefaultTieRod" "tci:DefaultWingnut" "tci:DefaultPushPullProp"	"4" "8" "8" "8"	"Lev1_loca(w)"	"2019-04-04 11:00:00.000"	"2019-04-08 07:28:48.000"	"NULL"	"NULL"	"NULL"	"0.0"
"585914"	"6.2"	"tci:DefaultPanel330x120" "tci:DefaultPanel330x240" "tci:TimberFilling"	"2" "4" "0.2"	"tci:DefaultCoupler" "tci:DefaultTieRod" "tci:DefaultWingnut" "tci:DefaultPushPullProp"	"4" "8" "8" "8"	"Lev1_loca(w)"	"2019-04-04 11:00:00.000"	"2019-04-08 07:28:48.000"	"NULL"	"NULL"	"NULL"	"0.0"
"640260"	"8.4"	"tci:DefaultPanel330x120" "tci:DefaultPanel330x240" "tci:TimberFilling"	"2" "6" "0"	"tci:DefaultCoupler" "tci:DefaultTieRod" "tci:DefaultWingnut" "tci:DefaultPushPullProp"	"8" "12" "12" "10"	"Lev1_loca(w)"	"2019-04-04 11:00:00.000"	"2019-04-08 07:28:48.000"	"NULL"	"NULL"	"NULL"	"0.0"

Table 4: Output table from querying combined graph

Chapter 5. Data Visualization and Distribution

The previous steps of prototyping a solution all intend to link existing data to a combined dataset that is able to provide a TCI utilization plan. After comparing the result with a professional calculation tool for formwork (PERI Quicksolve), it is assumed that the raw data is correct. Thus, the next crucial step of prototyping is to distribute the data to the target groups in the most convenient and accessible way. In this case, data visualization helps to bring the right amount and type of data to the specific target group.

As the output data is stored in RDF-triples in a triple store, there are several options on how to visualize the data, such as the use of a web application that directly queries the triple store. For the application in this thesis project, however, already existing and proven tools from the company Exigo A/S are used for data visualization and distribution. The first tool is a Power BI dashboard that is directly linked to a SQL database and receives updated schedule information through Exicute, the cloud platform with progress monitoring of Exigo A/S. As a second visualization tool, a new tab in the Exicute application is intended to display all required TCIs for each specific construction task. Similar to the "Quantities" tab, which shows the quantities of PCIs for each task, the new tab shall give updated information about the TCI utilization on site, broken down to the task level. The utilization of these visualization tools allows to integrate TCI information within an already established process, validated by the Danish construction industry. Thus, the adoption of the proposed solution within the construction industry is facilitated as it can come as an extended feature of an existing product.

5.1 SQL Conversion

In order to use both visualization tools, the data has to be converted into SQL format. For this purpose, a program (**indexRDF2SQL.js**) has been developed that receives the output data from the Fuseki triple store and writes it into common SQL tables via SQL Query language. Communication with the SQL database is enabled by the Microsoft SQL Server client for Node.js "mssql" which can be found with the following URL: https://www.npmjs.com/package/mssql #microsoft--contributors-node-v8-driver-for-nodejs-for-sql-server.

Based on the prototyping status of the solution, the following SQL tables are developed. These tables serve as the data source for the use of Power BI as well as the application Exicute, and thus must contain all necessary information to visualize the TCI utilization plan and meet the needs of the specific target group.

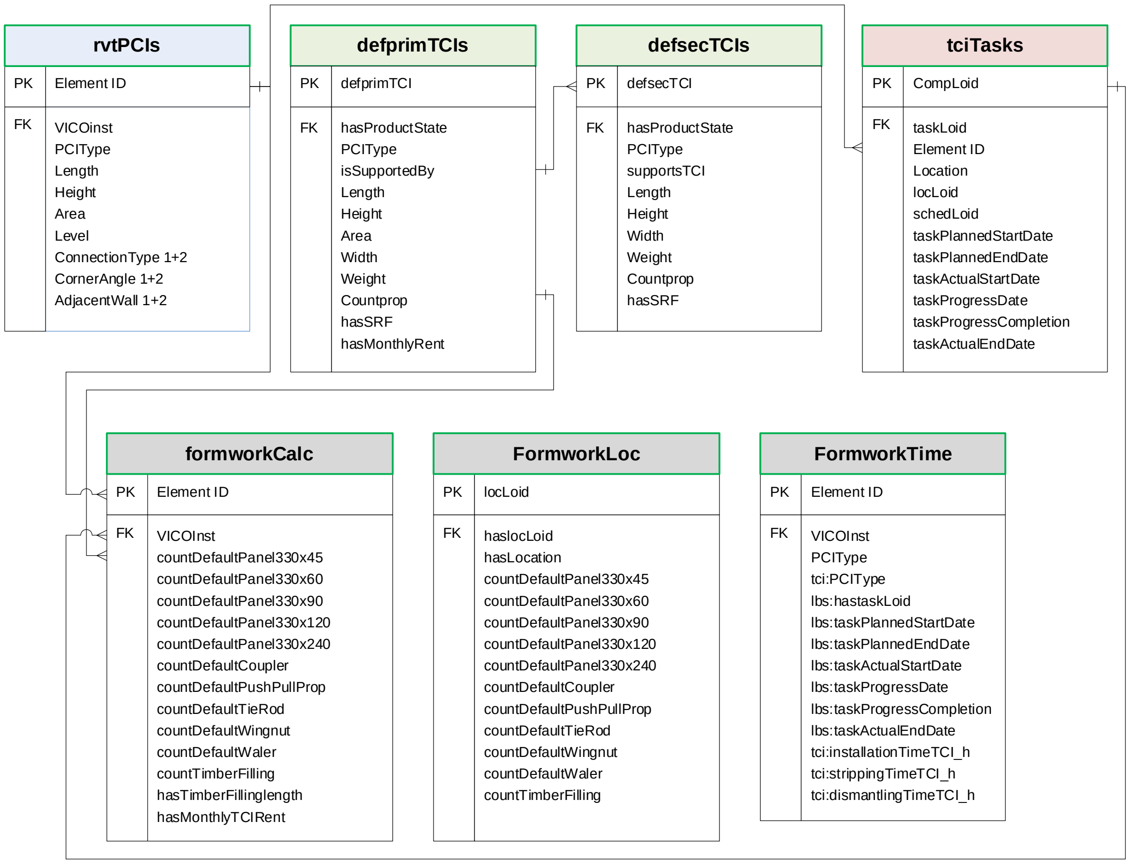


Figure 20: SQL tables for data visualization

5.2 Power BI

Power BI is a visualization tool from Microsoft that enables to build live dashboards, based on a huge variety of data sources, one being a SQL database. The direct link between the data and the dashboard allows to always have the updated data regarding the reviewed project. Power BI dashboards are mostly used to give a general overview of the current status and progress of the construction site regarding various aspects. Due to this superficial consideration, these dashboards are targeting the management perspective of a company.

Exigo A/S uses the dashboard among others to visualize the construction progress, a change order log, a risk calculation, a cashflow diagram as well as the resource allocation for the construction site. The following figure shows an example dashboard that is used as a template to create dashboards for visualizing the TCI data.

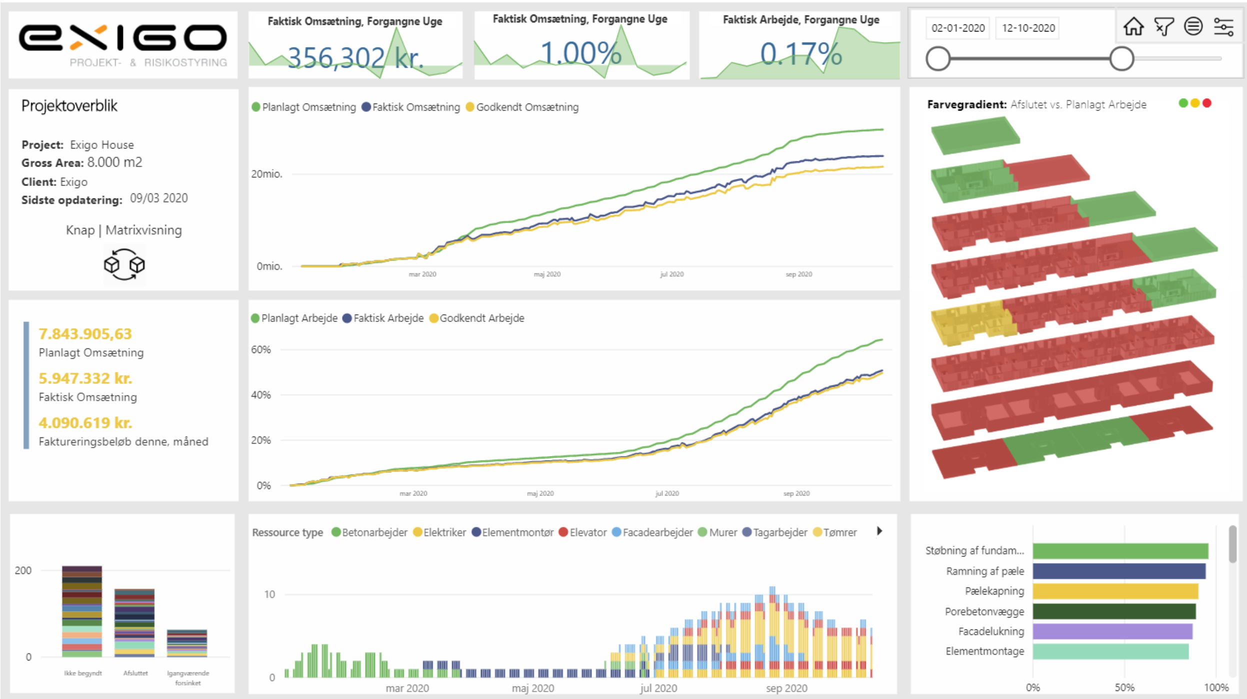


Figure 21: Example dashboard from Exigo A/S

In order to develop a new dashboard for the visualization of TCI data, some important aspects have to be considered. The following list provides all the features, the developed dashboard incorporates to visualize the TCI utilization plan.

- Exploded building view of the building model with different locations 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%)
- Graph showing an accumulated cost comparison of TCIs on the construction site, based on the comparison between the static stock and dynamic stock.

The comparison between the dynamic and static stock is an exemplary quantification of the benefits, the proposed solution generates for the construction project. Here, the current practice is compared to the approach, a contractor could pursue with the proposed solution. In current practice, as also identified in chapter 5.1, formwork elements are ordered, based on an estimation of what would be the peak amount of elements the construction site needs to have in order to meet the demand from the construction tasks. This peak amount of elements is then delivered by the TCI provider and stored on site. As it is dimensioned to cover the peak amount of formwork elements, the utilization of the elements for most working days is relatively low, resulting in a waste of money and storage space because the big and unused formwork panels are lying around on the construction site. In case the formwork is rented, this static stock approach leads to high costs in rent, which would be avoidable with a more dynamic stocking approach. In order to enable a dynamic stock, transparency about the TCI utilization on the construction site is needed early in construction to order the elements from the supplier in advance and to allow a just-in-time delivery. As the proposed solution provides this transparency, the construction site would benefit from a more dynamic formwork stock, which is continuously adjusted to the changes in the demand. If there is a high demand for a short period, more items are delivered to the site in advance to cover the demand and as soon as the demand decreases again, the surplus of formwork elements is returned to the supplier. This results in a generally much lower stock on site, meaning waste of money and storage space. Thus, the rent saving potential of the proposed solution shows a clear and quantifiable benefit for the construction site.

In the developed dashboard, besides the TCI Allocation and Quantities, this is the central information that is derived from the utilization plan and visualized in the dashboard. In the dashboard, this information is divided into a utilization comparison between the dynamic stock and the static stock as well as a cost comparison, showing the cost development over time for both the static and dynamic stock. The resulting dashboard, incorporating all mentioned features is shown below.

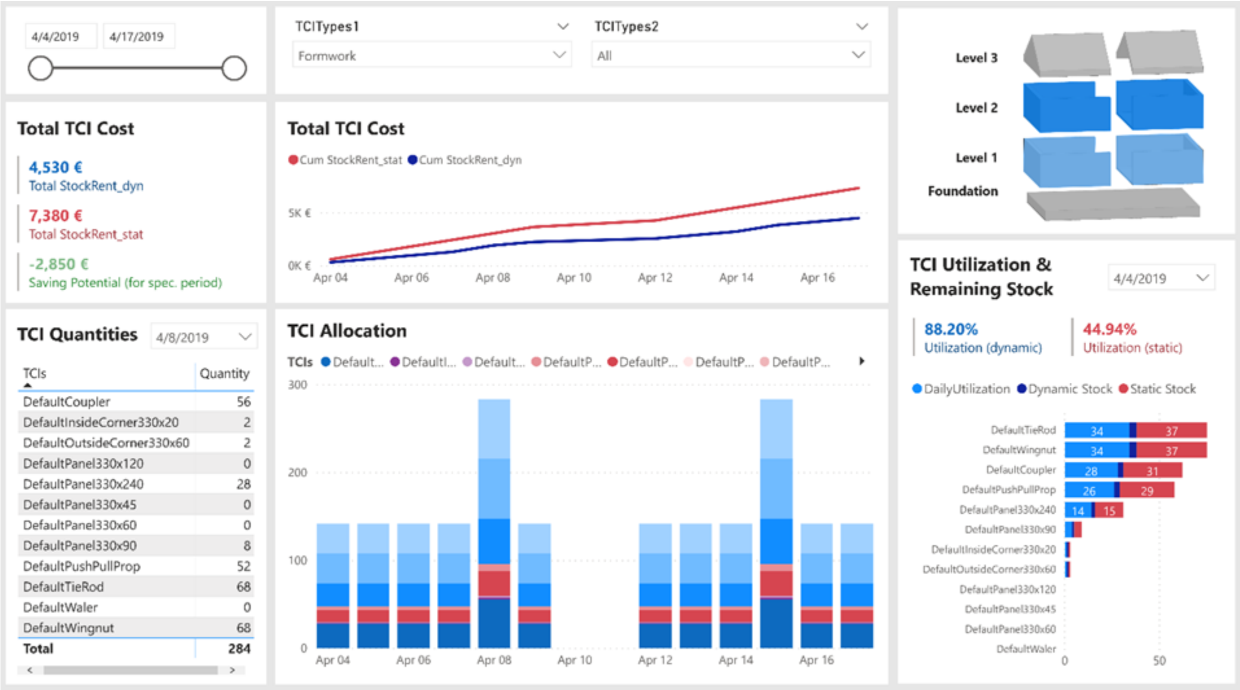


Figure 22: Demo Dashboard - *TCI Utilization*

5.3 Exicute Application

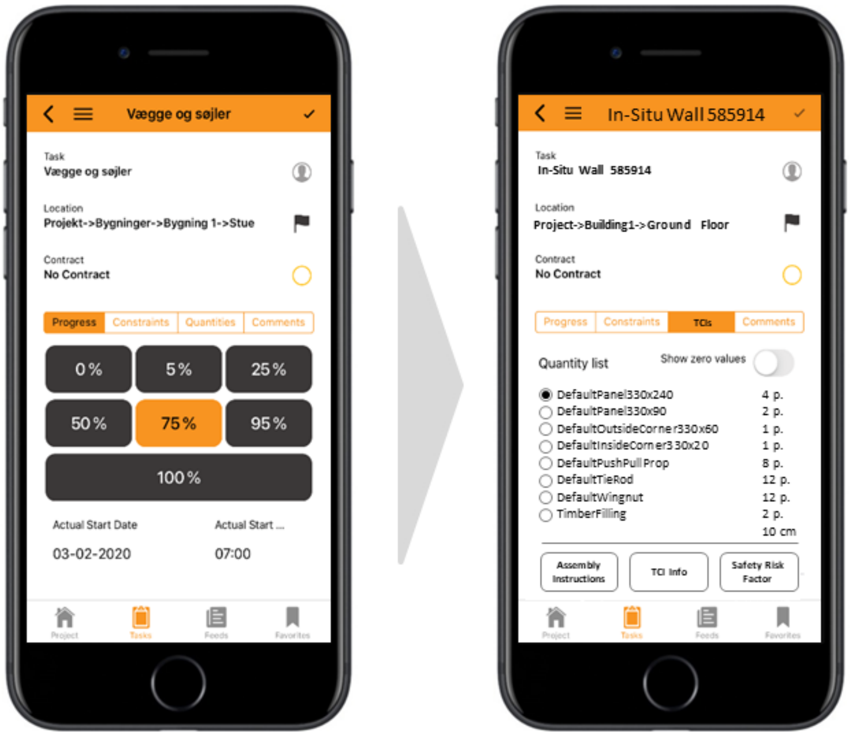


Figure 23: Interface of the Exicute App

The mobile application of Exicute is currently used to document the construction progress for each task. On a task-based level of detail, it shows the progress, constraints, quantities, and comments for each construction activity. A further development of the application with the implementation of the proposed solution could extend the shown information with a new tab, called "TCI Quantities". This tab could then return the required TCIs for each individual task of the construction project. In this tab, the required TCI quantities can be shown along with more detailed information about each TCI, e,g, with formwork: its weight, the time it needs to be installed and dismantled, the location to store the items before usage, the location where to bring the items for the next task as well as a safety risk factor which reveals TCIs that require special attention when installed and utilized. Assembly instructions for each task could also be included from the supplier to ensure safe and correct utilization of the elements. Integrating the TCI utilization into Exicute would add an additional feature to the product which allows the user to better plan and manage TCIs on the construction site. As an additional feature, it could be sold to contractors or clients to increase productivity and safety through a transparent TCI consideration in the project.

Chapter 6. Bibliography

Costa, G., & Pauwels, P. (2015). Building product suggestions for a BIM model based on rule sets and a semantic reasoning engine. *32rd International CIB W78 Conference, Proceedings*, 98–107.

Martin, B., & Hanington, B. M. (2012). *Universal methods of design: 100 ways to research complex problems, develop innovative ideas, and design effective solutions*. Beverly, Mass.: Rockport Publishers.

Appendix 4

Case Study Documentation

TECHNICAL UNIVERSITY OF DENMARK

PROTOTYPING – Case Study Documentation

APPENDIX 4

Thesis:	Unlocking the value of Linked Building Data (LBD) - A Lean and integrated management process of temporary construction items (TCIs)
Chapter:	Chapter 6.2 – Case Study
Method:	Case Study (Yin, 2014)
Purpose:	This Case Study documentation will serve as a protocol for the consecutive steps for applying the developed prototype solution in a real case construction project. The documentation is structured to continue the prototyping process from the demo project. First, it introduces the case project and reveals the current state of the prototype solution. Subsequently, the different steps of applying the prototype in the case project are presented. Concluding this documentation, findings of the case study are summarized in the last chapter.
Author:	Alexander Schlachter
Student number:	182781

Table of Content

List of Figures

List of Tables

Chapter 1. Introduction

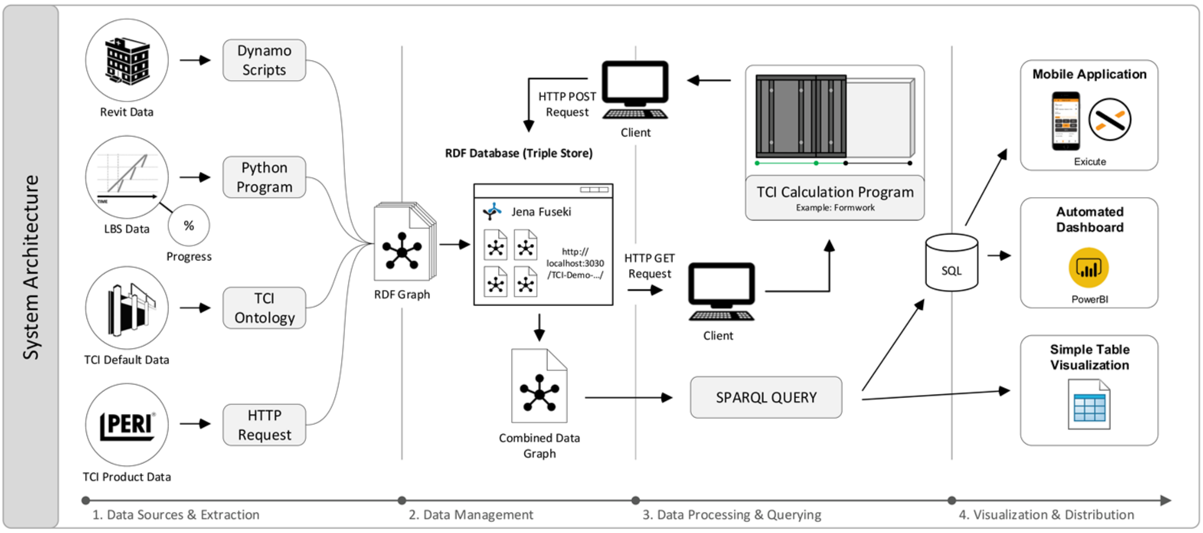


Figure 1: System Architecture of the proposed solution

The case study is part of the further development of the prototype and follows directly up on the first prototype phase, where the solution was developed with a small demo project. The case study is the second phase of prototyping and explores the applicability of the developed solution in a real case construction project and determine limitations and derive further developments of the prototype. The system architecture in figure 1 presents the solution workflow how it was developed for the demo project. In theory, the generic workflow should be applicable to all building projects with the same data sources. In the following paragraphs, the case study documentation tries to prove this assumption and documents the further development of the solution. First, the case study project is introduced in chapter 2. The focus lies on explaining the scope of the case study project as well as the different data sources, that are used. Furthermore, a further section verifies whether the simplifications of the prototype are still valid for the case study application. This will also outline the solution status that was applied in the case study. Following up on the case study introduction, chapter 3 of the case study documentation explores the different steps of applying the solution to the project. In chapter 4, the findings of the case study are derived from the application, which will explain the ongoing improvements that are made during the application as well as identify open issues and limitations of the solution. The last chapter then concludes the results of the case study.

Chapter 2. Case Study Project

By applying the prototype solution to a real construction project, the solution will be further developed, and its functionality is tested in a real construction project. In this case, the permission to use the project data was given by the public client Vejdirektoratet (The Danish Road Directorate) and the data, containing the 3D-Model and a location-based schedule, was provided by Exigo A/S. The case study is based on a public Danish construction project for a new healthcare science university faculty that is physically joint with the existing university and a new university hospital. The following table gives an overview of the project's main facts and characteristics:

Project Name	SDU SUND
Location	Odense
Project Type	Public, New Construction, Rural
Building Type	Healthcare Science Faculty
Building Size	50.740 m²
Levels	Basement, Level 1-4
Building Sections	45.1 – 45.6
Value for Case Study	In-situ concrete walls are installed in the basement and serve as an application field for the developed prototype solution, creating a utilization plan for the required formwork
Used Data	• 3D-model (rvt-file) • Location-based schedule (vico-file)

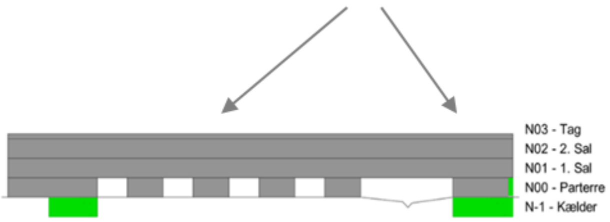
Table 1: Case Study Project Information

As seen above, the project is divided into six building sections, reaching from 45.1 to 45.6. The following orthographic picture of the construction site from the 24.05.2020 shows the layout of these sections from the north (left) to the south (right).

Figure 2: Orthographic picture with project sections

The focus of the case study will be on the in-situ concrete walls in the basement and ground floor level of section 45.1 and the basement level of section 45.6. In total, the project contains 19 different types of in-situ walls which are all located in the specified locations. Before the solution can be applied to simply all in-situ walls, the model has to be analyzed in order to find out, if those items are actually in-situ concrete walls. This analysis revealed that most of the walls, that are specified as in-situ concrete walls, are actually parts of foundation blocks, columns, or beams. Thus, the wall selection was reduced to only contain the in-situ concrete walls which form the structural system of the basement in section 45.1 and 45.6, resulting in three different wall types that are shown in the following figure.

In-situ walls in the project		
Type	**Location**	**Qty.**
VGY35	45.1 N-1 & N00 45.6 N-1	26
VGY39	45.6 N-1	3
VGY47	45.1 N-1 45.6 N-1	8



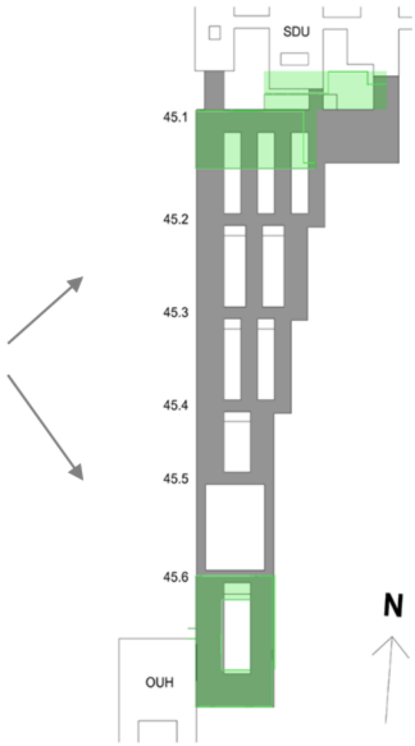


Figure 3: In-situ walls in the case study project

In the next chapter, the prototype solution is applied to these three wall types to first, calculate the formwork demand for each wall element and then generate a TCI utilization plan by linking it together with the location-based schedule. However, before going through the different steps of the case application, a verification is needed whether the case study project is aligned with simplifications of the premises that are defined for the prototype solution (see Appendix 3 – Demo-Project Documentation).

a) Formwork is chosen to represent all TCIs that can be linked to a model object

This simplification is possible with the project of the case study, as in-situ concrete walls are used in the basement of building 45.1 and 45.6 which are subject to this study.

b) One dimensional calculation of vertical formwork for the construction of concrete walls

As the wall height of the regarded in-situ walls in the case study range between 4.22 m and 5.22 m, two formwork elements with each 2.70 m are stacked on top of each other to cover all walls. Thus, the formwork quantities are slightly over-dimensioned in their height, due to this simplification.

However, as this approach also reflects the utilization of formwork elements on the actual construction site, where two stacked formwork elements of the height 2.70 m are used to cast all in-situ walls (see Appendix 2 - Photo Documentation of Site Observation), the simplification is regarded valid.

c) Height of forms is always greater than the wall height, hence no need for consideration of heights

As justified before, two stacked formwork elements with a total height of 5.40 m are calculated to cover the wall height of all regarded walls. Hence, the simplification is still valid, although the result might be optimized.

d) Utilization of only a default set of forms with specific parameters

For this thesis, the use of the default set of formwork is sufficient to justify a proof of concept as the integration of a confirmed formwork set from a selected provider is considered and can easily update the default utilization plan. The panel height of the default formwork set in this case study, in comparison to the demo project, is reduced to the standard height of 2.70 m, as a stacked approach is applied here.

e) Assumption that walls in the building model are modelled as they are constructed, meaning that the wall separation in the model represent the sequencing of the construction activity which must be covered by formwork

A total of 5 walls from the regarded set of in-situ walls are split by the location management system in VICO office. Therefore, the calculated formwork elements cannot be linked to a single element instance from VICO which contains the task time information. This means that two schedule tasks are applied two one wall of the building model and therefore, the formwork elements occur twice in the TCI utilization plan. As this issue only concerns 5 walls, the overall result is still regarded as valid. Considering the fact that the split walls result in false information in the TCI utilization plan, this issue is reviewed in chapter 4 of this documentation.

f) Corner panels are not considered in the demo project

This simplification was removed in the case study, as corner elements are now included in the proposed solution. More information is provided in the following chapter.

g) Formwork is calculated for the entire length of each modelled wall

As corner elements are included in the case study application, the formwork calculation is considered more realistically. If the wall contains a corner ending, the wall-length has to be reduced respectively with the length of the corner elements. If no corner is detected, walers and plywood should be applied at the end of a wall sequence to close the formwork system and prevent the concrete from pouring out. Thus, the formwork covering has to reach slightly over the actual wall length to apply the plywood and walers. The consideration of the wall sequence however requires to already integrate the schedule information in the calculation process of the formwork elements in order to know where to close the formwork system, and this has not yet been done in the prototype solution. Hence, the status of the prototype solution, which is applied to the case study, calculates a full range of formwork elements for the given building elements but does not consider the formwork sequence.

After verifying the prototype simplifications and presenting the current status of the solution, that is applied to the case project, the documentation provided sufficient introduction to go through the steps of the case application. During the application, the prototype is further developed and adjusted to fit the needs of a real construction project. These adjustments are documented as well in the following chapter.

Chapter 3. Case Application

This chapter explores the four different steps of the system architecture which were applied to the case project. As the solution framework was already explained in detail in the demo-project documentation, this chapter will focus on the specific application on a big scale project and the adjustments and further development of the solution during the case application. Captures of the results are presented in this documentation and the whole content of the case study and all developed programs and tools can be found in the GitHub repository LBD-for-TCI (https://github.com/Alex-Schlachter27/LBD-for-TCI/tree/master).

The next chapter will then reflect on the case study findings and draw a conclusion.

3.1 Data Sources & Extraction

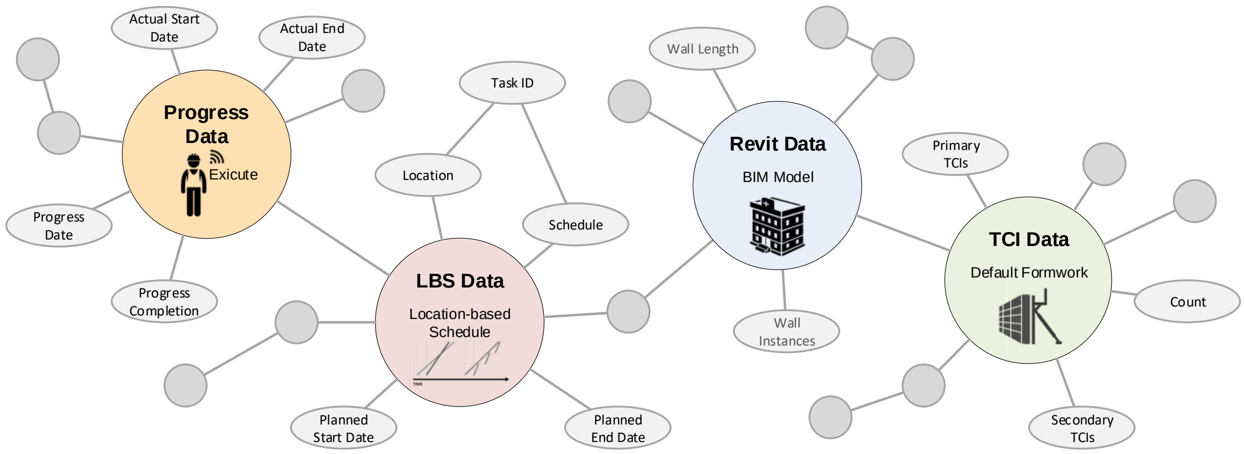


Figure 4: Data Sources with desired parameters

Figure 4 shows the different generic data sources, which are integrated into the prototype solution. In the case study, the dataset of TCIs is almost the same as the dataset in the demo project, providing the required information of the primary and secondary formwork elements in the default formwork set. The only difference is that, apart from the formwork panels, the primary formwork elements also contain standard corner elements. This allows to calculate the formwork demand more holistically and realistically, representing the real demand on the construction site. Furthermore, as mentioned earlier, the height of the formwork panels is now set to 2,70 m.

The building model of the project is a structural model, modelled in Revit, and containing all structural elements of the project. In order to only extract the walls, that are regarded in this case study, the Dynamo scripts are modified to extract only the information of the wall types VGY35, VGY38, and VGY47 (See figure 5).

Figure 5: Capture of 3D-view of the Revit model, only showing the regarded in-situ walls

This modification is applied to all Dynamo scripts that are extracting the model data, convert it into RDF-triples and write it directly to the triple store Jena Fuseki to create the Revit data graph for the case study. The following picture shows a capture of the Dynamo script that assigns the wall types to the RDF class.

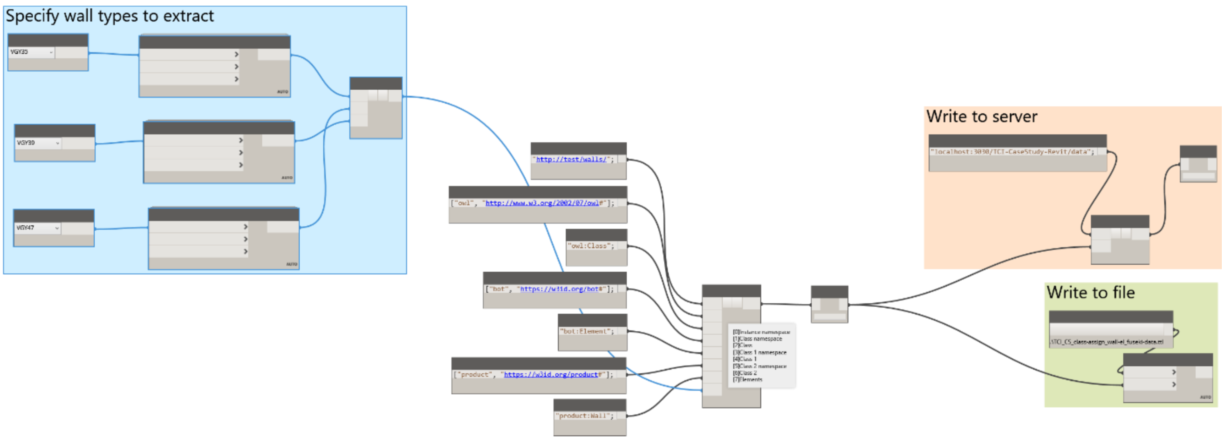


Figure 6: Dynamo script, extracting the regarded wall types

Figure 6 shows the resulting Revit graph in RDF.

```
wallinst:ef24efa4-4fef-4d22-b807-03a3af66a712-00bb15f6
        a                     product:Wall ;
        tci:pciType           product:Wall ;
        bot:adjacentElement   wallinst:ef24efa4-4fef-4d22-b807-03a3af66a712-00bb144c ,
                              wallinst:ef24efa4-4fef-4d22-b807-03a3af66a712-00bb16e9 ;
        props:Element_ID      "12260854" ;
        props:Revit_GUID      "ef24efa4-4fef-4d22-b807-03a3af66a712-00bb15f6" ;
        props:angle           90.0 ;
        props:area            38.18 ;
        props:building        "45.1" ;
        props:height          4.69 ;
        props:length          8.31 ;
        props:level_simple    "N00" ;
        props:wallType        rvt:Vgy35 .
```

Figure 7: Excerpt of the resulting Revit data graph showing one wall instance

The location-based schedule (LBS) of the project was established by Exigo A/S in the software VICO Office and contains schedule and location information of the whole project. This schedule is based on the same Revit model, and thus the same wall instances can be found in the dataset of the Revit model and the schedule. For the case study application, the schedule is not modified or adjusted to meet the requirements of the proposed solution. On the contrary, the intention is to use a common schedule as it is used in current construction projects. With this approach, the functionality of the solution can be proven, and potential limitations and further developments can be addressed based on the findings.

Figures 8 and 9 show captures of the LBS information from VICO Office. Figure 8 contains the flow-line view and figure 9 presents the location management system, which is dividing the building elements into different locations, that are used to create the schedule.

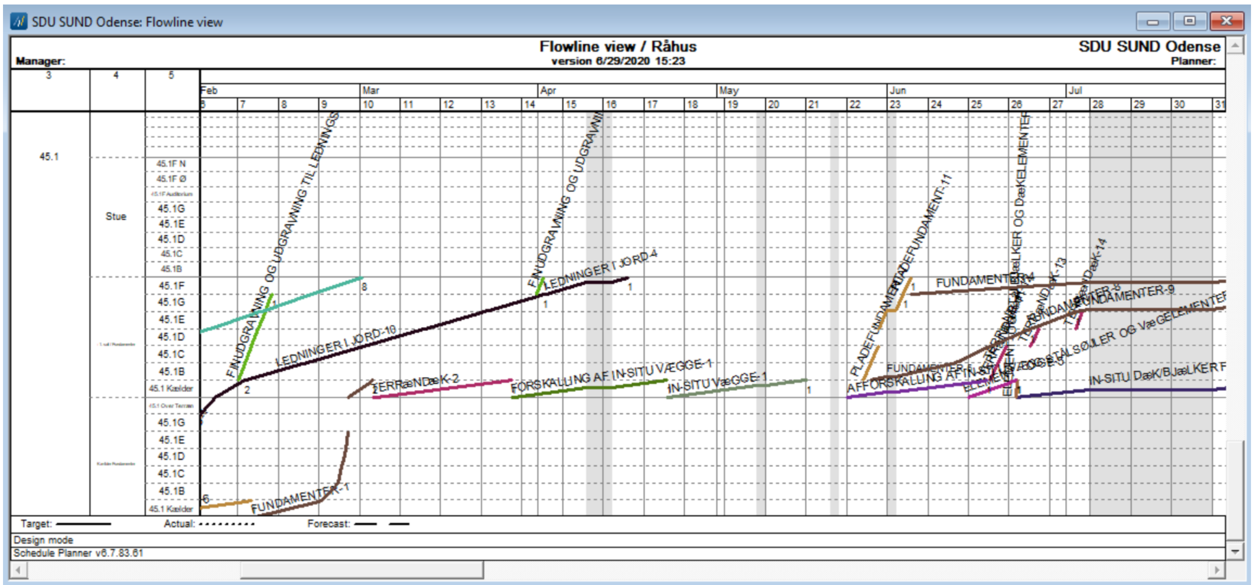


Figure 8: Location-based schedule of the case study project

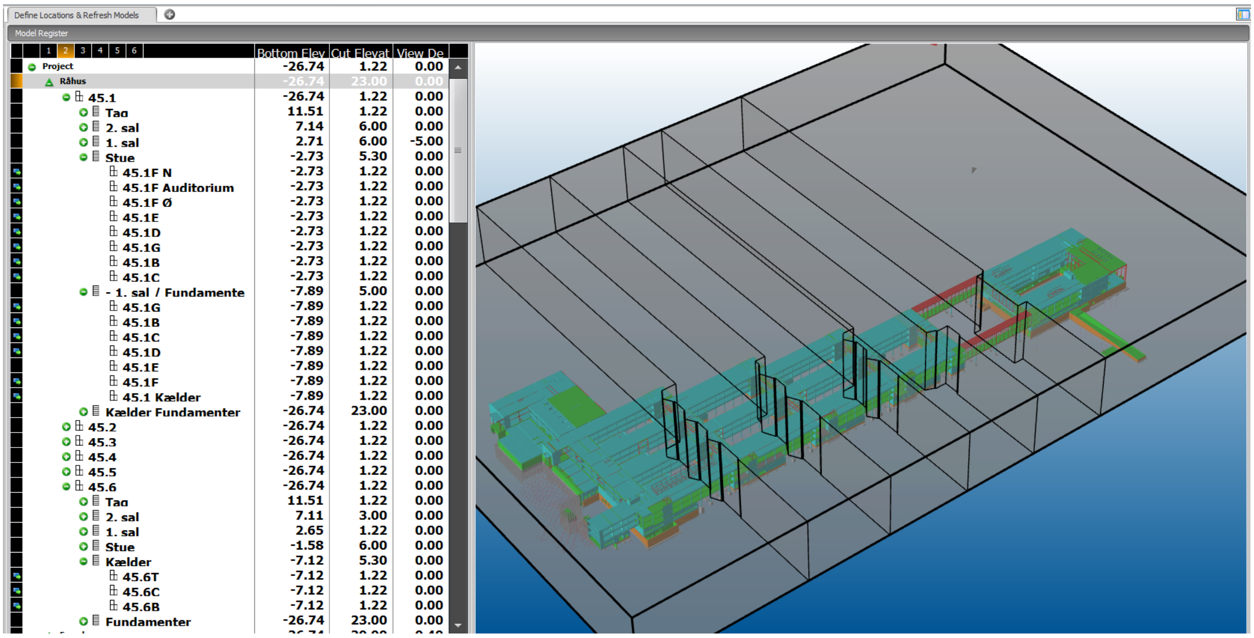


Figure 9: Location Management System of the case study project

As mentioned in the Demo-Project Documentation, a manual extraction of the LBS data was chosen for simplification as the data was quite small and handy. For a real construction project, this would require a lot of effort and would not fit in the scope of the thesis. Thus, a solution had to be developed to write the LBS data from VICO into the triple store. The solution to this problem is two-folded.

The first intention for bringing the information from VICO to the triple store was to use the software ExiLink from Exigo A/S, which was already introduced in the Demo-Project Documentation. This tool is based on a python code, that is able to go through the different datasets (Figure 10) of the VICO project, extracts the required schedule information, and writes the data in an SQL database. The structured data from the SQL database can then easily be converted into RDF-triples with an appropriate python script.

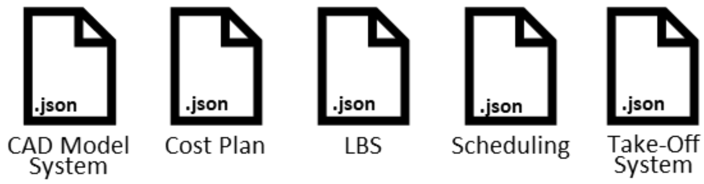


Figure 10: Datasets of the VICO project as JSON-files

As the software was more explored and workshops were held with employees from Exigo A/S, it was identified that ExiLink is only taking a few datasets from VICO in order to establish the schedule information. These datasets are "Cost Plan", "LBS" and "Scheduling" and contain all information for displaying the LBS-data in the solution of the company. The specific application in the thesis, however, requires to include the Element IDs of the wall instances in the building model in order to link the instance code of the LBS data to the same code in the Revit data.
Therefore, an additional program (**VICO-Extraction-Program.py**) has to be developed which is extracting the missing information from the VICO datasets and write it to the SQL-database. From there, the additional data, with the already existing schedule information, can be converted into RDF triples, transferred to the triple store, and integrated into the LBS data graph of the case study. This is being done with the program **VICO_SQL2RDF.js**. The key relationship between the instance code of the wall elements and the schedule information is the taskLoid, which is a generated instance code for each task. This task can be described with an individual combination of the location (locLoid) and the cost item (compLoid) in the VICO project as both items are used to create the schedule tasks and one specific location cost-item relation only describe one single task item. This means, that each task in the LBS-System can be described with the information of the location and cost-item. Furthermore, the compLoid of the cost item can be directly referenced to the wall instances that are summarized into one cost item.

Hence, the program has to extract information that contains the wall instances, as well as its relation to the compLoids and locLoids as the combination of both codes, is the key to link the wall instances to the schedule information.

The Element ID, that are originally created in Revit, are stored in the dataset "CAD Model System" and are summarized into take-off items of the same element type in the "Take-Off System". In this dataset, each wall instance in a take-off item also contains information about its location. Hence, the locLoid can be extracted in this step. The take-off items can also be found in the "Cost Plan" as they are directly linked to a cost item which is described by the compLoid. Going through the datasets "CAD Model System", "Take-Off System" and finally "Cost Plan", the developed Python-program (**VICO-Extraction-Program.py**) is able to create a SQL-table that includes the Element ID of the wall instances, the locLoid as well as the compLoid in order to link the wall instances to the tasks of the location-based schedule. This relationship between the VICO datasets is also visualized in the following figure.

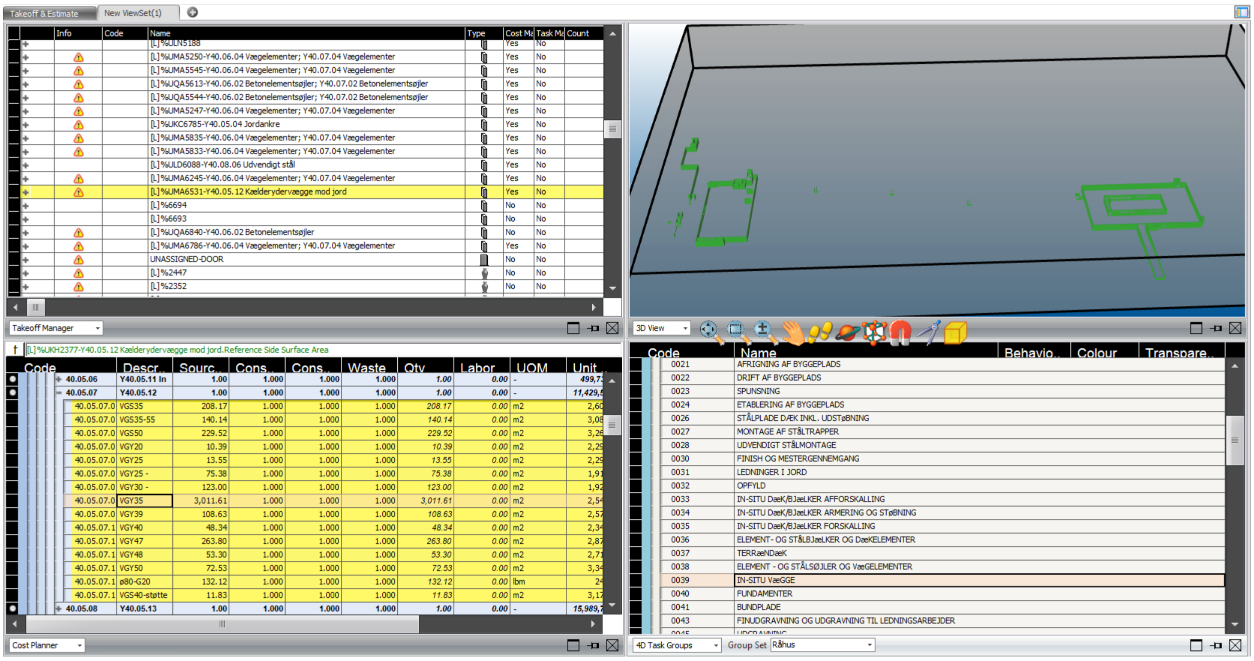


Figure 11: VICO Office interface in the case study project

Figure 11 shows the VICO Office interface with the four windows Take-Off Manager (containing the take-off items), Cost Planner (containing the cost items), and 4D Task Groups (containing the tasks). On the screen, the wall type VGY35 was selected in the Cost Planner and as it is linked to the other datasets, all items that are related to the selected wall type, are highlighted in yellow.

This proves the previously explained relation of the different datasets in the LBS software VICO. A capture of the resulting SQL-table is presented in figure 12.

ElementID	rvtGUID	locloid	toi	comploid
2927850	{13eb2559-6889-4e8e-9f20-6bb21ea0b923-002cacea}	15299.0.4232	15300.0.2227937	15300.0.98617492
2927850	{13eb2559-6889-4e8e-9f20-6bb21ea0b923-002cacea}	15300.0.45032304	15300.0.2227937	15300.0.98617492
2927850	{13eb2559-6889-4e8e-9f20-6bb21ea0b923-002cacea}	15300.0.53166144	15300.0.2227937	15300.0.98617492
2927850	{13eb2559-6889-4e8e-9f20-6bb21ea0b923-002cacea}	15300.0.53166171	15300.0.2227937	15300.0.98617492
2927850	{13eb2559-6889-4e8e-9f20-6bb21ea0b923-002cacea}	15300.0.53177359	15300.0.2227937	15300.0.98617492
2927850	{13eb2559-6889-4e8e-9f20-6bb21ea0b923-002cacea}	15300.0.53179181	15300.0.2227937	15300.0.98617492
2927850	{13eb2559-6889-4e8e-9f20-6bb21ea0b923-002cacea}	15300.0.38238460	15300.0.2227937	15300.0.98617492
2927851	{13eb2559-6889-4e8e-9f20-6bb21ea0b923-002caceb}	15299.0.4232	15300.0.2227937	15300.0.98617492
2927851	{13eb2559-6889-4e8e-9f20-6bb21ea0b923-002caceb}	15300.0.45032304	15300.0.2227937	15300.0.98617492
2927851	{13eb2559-6889-4e8e-9f20-6bb21ea0b923-002caceb}	15300.0.53168889	15300.0.2227937	15300.0.98617492

Figure 12: Resulting SQL-Table, containing the Element ID, locLoid and compLoid

As revealed in figure 12, one wall instance contains several locations. This is because VICO is assigning the wall instances to all the hierarchy levels of each location systems (shell construction and façade), the wall is located in. Therefore, each locLoid represents a different hierarchy level. In this application, however, only the lowest hierarchy level of the shell construction (Råhus) matters. This aspect is considered subsequently.

In the next step of the case study, the SQL-data, containing all required schedule information, is converted into RDF-triples and written into the LBS data graph of the triple store. Therefore, a Javascript-Program (**VICO_SQL2RDF.js**) was developed, which is able to communicate with the triple store, similar to the TCI calculation program that was developed in the demo project. Now instead of receiving the data from the triple store, calculating the TCI demands, and writing the results back to the triple store, the new program is receiving the SQL-data, converts it into RDF-triples and writes it to the empty LBS data graph. In this program, it is also specified that only the lowest hierarchy-level of the shell construction location system is considered. Furthermore, the program combines the datasets which were extracted through ExiLink with the dataset with wall instances by matching the located cost-items. By that, the wall instances are linked to the schedule tasks, which means that the LBS data graph contains all the required information for creating the TCI utilization plan by linking it to the other datasets in the Linked Data environment. Figure 15 is summarizing the data extraction process from the VICO datasets to the RDF data graph.

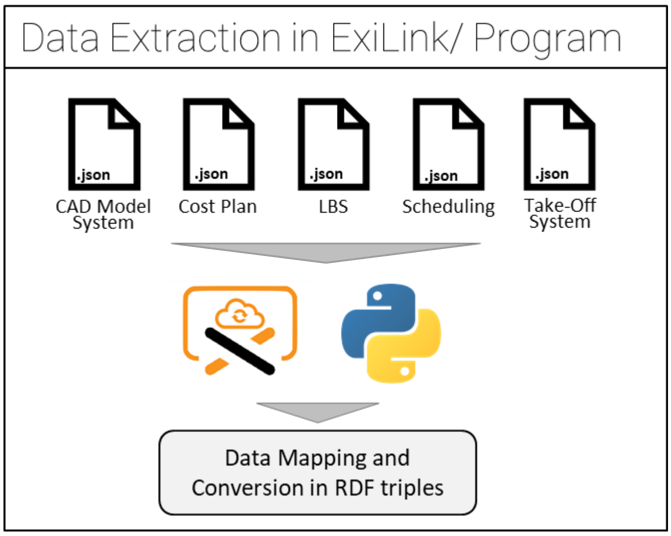


Figure 13: Visualization of the data extraction from VICO in the case study

Figure 14 is completing the data extraction from VICO, showing the resulting LBS data graph.

```
vicoinst:15300.0.104740129
        a                            lbs:VICOelement ;
        lbs:description              "Vgy35" ;
        lbs:elementType              "DERIVEDELEMENT" ;
        lbs:hasCompLoid              "15300.0.98617492" ;
        lbs:hasElementLoid           "15300.0.104740129" ;
        lbs:hasLocation              "45.1f n" ;
        lbs:haslocLoid               "15300.0.38277190" ;
        lbs:hasprojectGUID           "2e060258-64b3-41e5-b132-29d5a14ceb9f" ;
        lbs:hasschedLoid             "15300.0.99034466" ;
        lbs:hastakeOffID             "15300.0.2227937" ;
        lbs:hastaskLoid              "15300.0.99143062" ;
        lbs:hastaskName              "In-situ vÃ¦gge" ;
        lbs:taskActualEndDate        ""^^xsd:dateTime ;
        lbs:taskActualStartDate      ""^^xsd:dateTime ;
        lbs:taskPlannedEndDate       "2020-11-11T11:07:12Z"^^xsd:dateTime ;
        lbs:taskPlannedStartDate     "2020-11-06T07:57:57Z"^^xsd:dateTime ;
        lbs:taskProgressCompletion   "0"^^xsd:nonNegativeInteger ;
        lbs:taskProgressDate         ""^^xsd:dateTime ;
        props:Element_ID             "12260854" ;
        props:Revit_GUID             "{ef24efa4-4fef-4d22-b807-03a3af66a712-00bb15f6}" .
```

Figure 14: Excerpt of the resulting LBS data graph

3.2 Data Management

This chapter is exploring the data management of the proposed solution for the case study application. As data management is the same as in the first phase of the prototyping, it can be reviewed in detail in Appendix 3 – Demo-Project Documentation. The approach to combine the data in the triple store is still done manually, as the remote controlling engine called "comunica", which should allow executing SPARQL queries remotely in a Javascript-Program could not be implemented successfully.

3.3 Data Processing & Querying


```
{ wallinst: 'http://test/walls/38c866f8-c24e-4a2f-9c4c-fb0dadc921e6-0084ca43',
  ID: '8702531',
  length: 6,
  angle: 90,
  adjacentElements: [
    'http://test/walls/38c866f8-c24e-4a2f-9c4c-fb0dadc921e6-0084cab7',
    'http://test/walls/687443c2-11cd-4bb3-8210-54c6bfdfa10f-008b1e5c'],
  TCIsIn: [
    { TCIinst: 'http://test/tci/DefaultPanel270x240_0', length: 2.4 },
    { TCIinst: 'http://test/tci/DefaultPanel270x240_1', length: 2.4 },
    { TCIinst: 'http://test/tci/DefaultPanel270x240_2', length: 2.4 },
    { TCIinst: 'http://test/tci/DefaultPanel270x240_3', length: 2.4 },
    { TCIinst: 'http://test/tci/DefaultPanel270x120_0', length: 1.2 },
    { TCIinst: 'http://test/tci/DefaultPanel270x120_1', length: 1.2 }],
  TCIsOut: [
    { TCIinst: 'http://test/tci/DefaultPanel270x240_0', length: 2.4 },
    { TCIinst: 'http://test/tci/DefaultPanel270x240_1', length: 2.4 },
    { TCIinst: 'http://test/tci/DefaultPanel270x240_2', length: 2.4 },
    { TCIinst: 'http://test/tci/DefaultPanel270x240_3', length: 2.4 },
    { TCIinst: 'http://test/tci/DefaultPanel270x120_0', length: 1.2 },
    { TCIinst: 'http://test/tci/DefaultPanel270x120_1', length: 1.2 }],
  secTCIs: [
    { TCIinst: 'http://test/tci/DefaultCoupler', weight: 4.58 },
    { TCIinst: 'http://test/tci/DefaultTieRod', weight: 4.43 },
    { TCIinst: 'http://test/tci/DefaultWingnut', weight: 2.58 },
    { TCIinst: 'http://test/tci/DefaultPushPullProp', weight: 22.8 }],
  TCIsCount: [
    { TCIinst: 'http://test/tci/DefaultPanel270x240', Count: 8 },
    { TCIinst: 'http://test/tci/DefaultPanel270x120', Count: 4 },
    { TCIinst: 'http://test/tci/TimberFilling', Count: 0 },
    { TCIinst: 'http://test/tci/DefaultCoupler', Count: 44 },
    { TCIinst: 'http://test/tci/DefaultTieRod', Count: 20 },
    { TCIinst: 'http://test/tci/DefaultWingnut', Count: 20 },
    { TCIinst: 'http://test/tci/DefaultPushPullProp', Count: 6 },
    { TCIinst: 'http://test/tci/DefaultPanel270x90', Count: 0 },
    { TCIinst: 'http://test/tci/DefaultPanel270x60', Count: 0 },
    { TCIinst: 'http://test/tci/DefaultPanel270x45', Count: 0 },
    { TCIinst: 'http://test/tci/DefaultInsideCorner270x20', Count: 0 },
    { TCIinst: 'http://test/tci/DefaultOutsideCorner270x55', Count: 0 },
    { TCIinst: 'http://test/tci/DefaultWaler', Count: 0 }],
  TimberFilling: [
    { TCIinst: 'http://test/tci/TimberFilling', Length: 0 },
    { TCIinst: 'http://test/tci/TimberFilling', Length: 0 }],
  Connections: [
    { wallinst: 'http://test/walls/38c866f8-c24e-4a2f-9c4c-fb0dadc921e6-0084cab7',
      ConnectionType: 'horizontal',
      angle: 0 },
    { wallinst: 'http://test/walls/687443c2-11cd-4bb3-8210-54c6bfdfa10f-008b1e5c',
      ConnectionType: 'horizontal',
      angle: 0 }],
  MonthlyRent: '5040.00',
  installationTimeTCI_h: '3.00',
  strippingTimeTCI_h: '12.00',
  dismantlingTimeTCI_h: '3.00' }
```


Figure 15: Output JSON Object of the TCI calculation program

Figure 15 shows the output JSON object of the TCI calculation program. The program itself is only slightly modified, compared to the version in the demo project, as it can now include corner elements. Two default corner elements are included in the dataset - DefaultInsideCorner270x20 & DefaultOutsideCorner270x55. In order to visualize the result of the TCI calculation program, the following figure shows an example wall structure, where the formwork elements are applied.

Each comment field contains information about the wall instance and type as well as its demand for primary formwork elements.

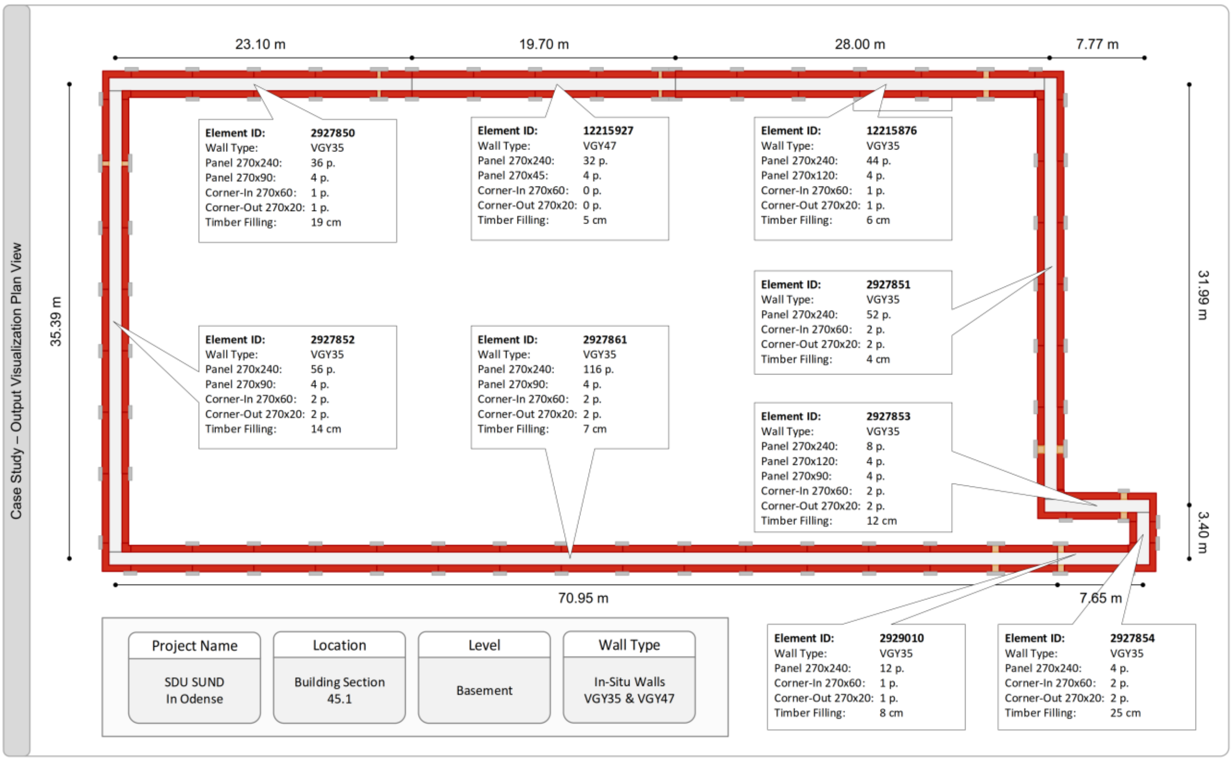


Figure 16: Output visualization plan view

In 3D, the formwork calculation can be imagined as figure 17 illustrates.

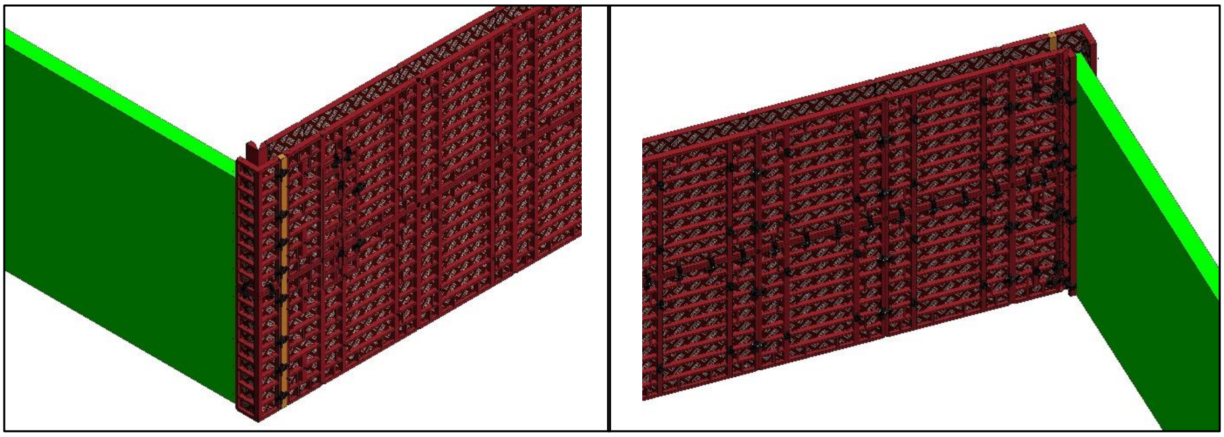


Figure 17: 3D-visualization of the formwork calculation

The program is then writing the data back to the triple store, where a combined data graph is generated out of the just calculated TCI quantities and the three datasets Revit data, LBS data, and TCI data. As in the demo project, this rich dataset can then be used to further visualize the data according to the needs of the relevant stakeholder who will benefit from the solution.

3.4 Data Visualization & Distribution

First, the data has to be transferred to the SQL database, which is used to link the data to the visualization tools. As visualization tools, the Exicute mobile application, as well as the Power BI dashboard, are selected again as in combination, the tools are able to reach all relevant stakeholders, who are in need of the TCI utilization plan, with a tailor-made visualization.

In contrast to the Power BI dashboard, which was further developed and improved, the Exicute App is still only a conceptualization based on a wireframe. The actual effort of developing the app extension to include TCI quantities for each regarded task is not an issue as the platform that is using data from the SQL-database is already existing. The actual issue is that the Exicute platform is still under development and therefore, a consistent app extension could not be developed within the scope of the thesis project. However, the concept of using the data also in a mobile app for the construction workers is still considered as a valuable extension to the developed solution.

In the case study application, more focus was put into the further development of the Power BI dashboard, as this visualization allows to include much more valuable insights into the TCI utilization plan, which will benefit the project or site manager on the construction site. Compared to the already existing dashboard from the demo project, two more pages were developed to give more insight into the developed project data and maximize the added value. The following list provides all the features, the new dashboard incorporates to visualize the TCI utilization plan.

- Project overview and dashboard content
- Exploded building view of building model with different locations 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%)

- 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 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 progress of the task (if received from the construction site)

The list of important aspects to include in the Power BI visualization resulted in the development of a four-paged dashboard that provides all necessary information regarding TCIs from a management perspective. The following figures subsequentially show the four dashboard pages and explain the content.

Figure 18: Dashboard Page 1 - *Project Overview*

Figure 18 presents the first page of the dashboard, giving a project overview, and providing insights into the following three main pages. The first page is only a static information box, that provides the user with project information on the left side of the page and with the content of the dashboard on the right side. Here, three pages are listed, containing all the above-mentioned features to visualize the full content of the TCI utilization plan. The content of these pages is explained below.

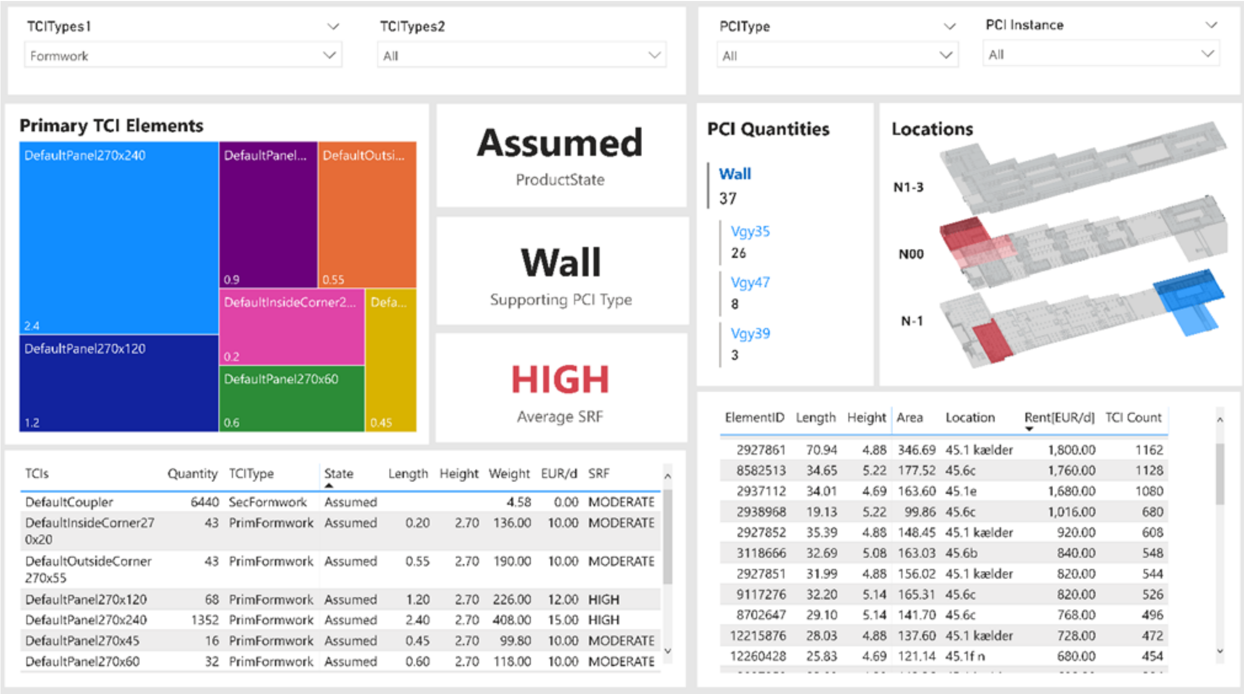


Figure 19: Dashboard Page 2 – *TCIs/PCIs*

Figure 19 shows the second page, the user finds when reviewing the Power BI report. This page is divided into two sections – left and right – and provides information about the temporary construction items (TCIs) as well as permanent construction items (PCIs). The left-hand side of this page reveals the type and some other useful information of all the formwork elements, which are used in the case study project. It also gives some clear notes about the product state of the used TCIs, which PCI they are supporting, and what average Safety Risk Factor the formwork elements have. On the right-hand side of the page, a list of all PCIs which are constructed in the project and supported by the TCIs during the construction activities is provided. In this case, all included PCIs are wall elements. Furthermore, the dashboard provides information about the wall types and their quantities in the project as well as the location, the walls are constructed.

This page shall give the user an initial overview of what TCIs as well as PCIs are used to create the TCI utilization plan, in order to better understand and analyze the next page, which is the main page of the developed dashboard.

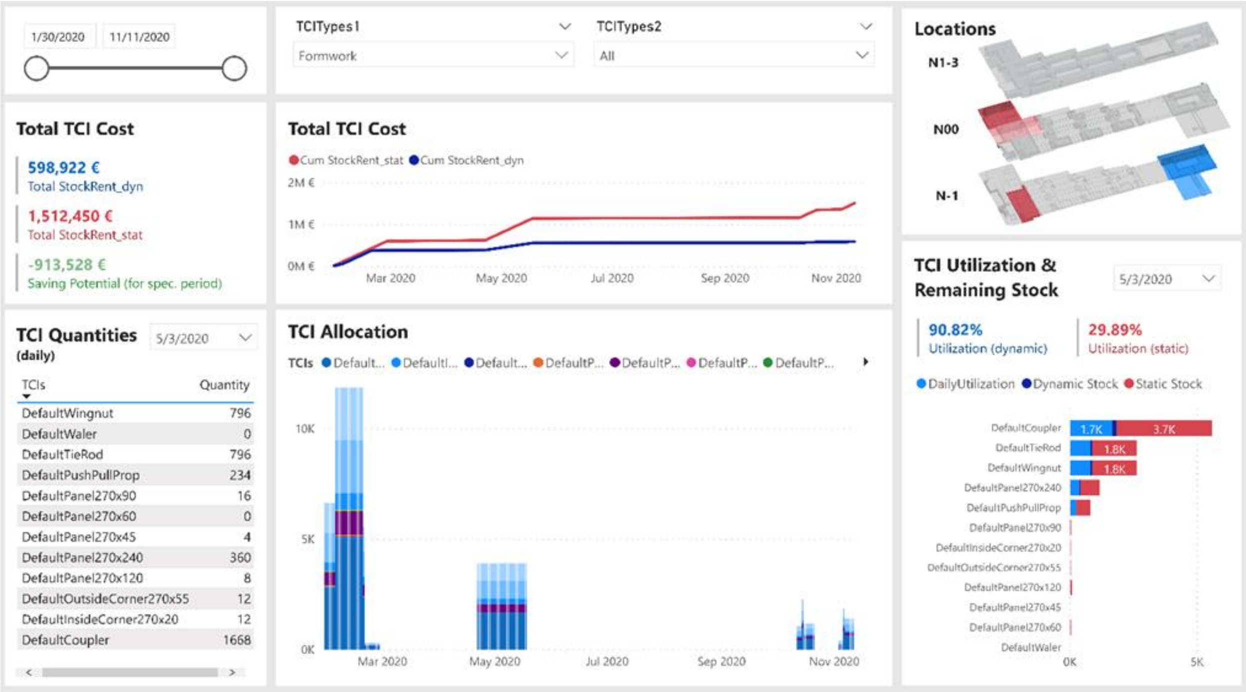


Figure 20: Dashboard Page 3 – *TCI Utilization*

Figure 20 contains the main page of the dashboard, which is exactly the same dashboard that was already developed in the demo project, now only containing the data of the case project. In the central position, the dashboard provides an overview of the TC utilization over time for the whole construction period. It takes into account each day, the tasks that are scheduled that day, the building elements that this task contains as well as the calculated TCI-demand of each building element. Thus, it gives a clear overview of what TCIs are needed on each project day on the construction site. As the solution is also built on a location-based schedule, a location filter on the upper right side of the dashboard allows two either select a location to receive the tasks and TCI quantities for this specific location or the user can select one specific day in order to specify the TCI quantities of this day as well as where the tasks of this day are located on site. On the lower left side, a simple table also reveals the TCI quantities of each day, if the user simply wants to check what items are needed on a specific day.

A further consideration that was already introduced in the demo project is the comparison between a static and dynamic stock of formwork elements. The static stock represents the current practice in the construction industry, where the site manager is ordering formwork elements based on his estimation and with the intention to cover the estimated peak amount of formwork demand plus a contingency buffer.

This approach leads to high quantities of formwork elements on site, costing avoidable rent and also use up valuable space on the construction site. In contrast, the proposed solution enables a dynamic stock with a just-in-time delivery approach, where the communication with the TCI provider is enhanced and formwork elements are ordered and delivered as they are needed on site. This results in a much lower number of formwork elements on site, saving money space and time. And all as a result of the created transparency of the TCI utilization.

This comparison is shown in three different parts of the dashboard. On the lower right side, the dashboard contains the TCI utilization in percent of a specific date, considering both the static (red) and dynamic (dark blue) stock approach. The second part in the upper center of the dashboard, a cost comparison over time shows the different cost development of both stock approaches, clearly identifying lower total costs of renting formwork elements with the dynamic approach. Just left to this, another visual presents the total costs of both approaches for the whole project as well as the potential savings in rent, a construction site could generate by implementing such a dynamic stock for formwork elements.

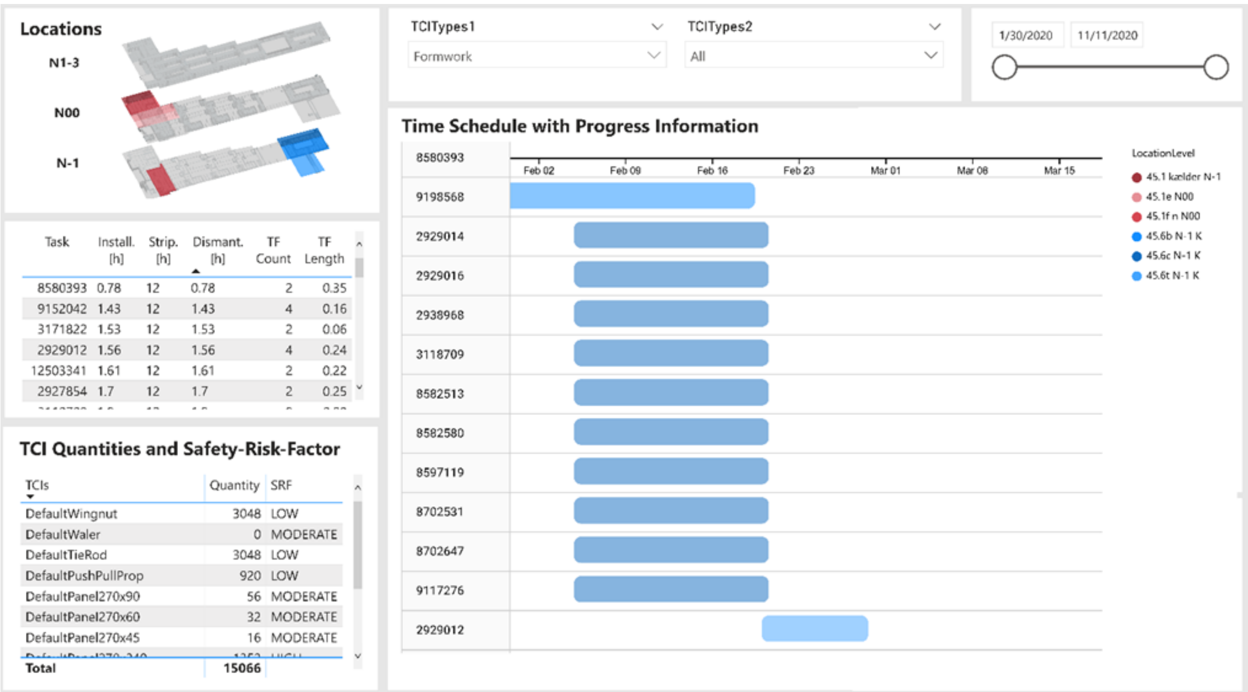


Figure 21: Dashboard Page 4 – *TCI Tasks*

The last page of the developed dashboard in the case study is presented in figure 21, containing similar information as the last page, but visualizes it in another way. This dashboard incorporates a Gantt-diagram to easily select a specific task and then receive the TCI-quantities as well as its location, shown in the dashboard. In addition to this main feature, the TCI quantity table also contains a Safety-Risk-Factor (SRF) which identifies the TCI items that are most risky to install, mostly because of their size and weight. In the center-part of the left side, a small table also shows information of each task, how much time it takes to install the formwork elements, how long the concrete has to rest until the formwork can be dismantled again, and finally how long it takes to dismantle the elements again. This calculation is based on the number of formwork elements and the volume of the wall. For a more precise formwork time consideration, other factors as the concrete type and weather conditions should be considered.

In conclusion, the developed three-folded dashboard with an additional overview page is a powerful tool for visualizing the TCI utilization plan. It clearly targets the management perspective of a contractor who is receiving an easily understandable and visually appealing presentation of location and time-based TCI-information in order to better plan and manage the construction site.

Chapter 4. Findings & Conclusion

In the previous chapter, the case application of the proposed solution was discussed in detail and all aspects and benefits of the further developed prototype were presented. However, the case study also identified some limitations and issues of the proposed prototype solution. By presenting these limitations and issues but also mentioning positive findings from the application on a real construction project, this chapter concludes the case study documentation with an objective reflection of the current prototype status.

Firstly, the case study application was successfully determined with the proof that the developed prototype is applicable to a real case construction project. All steps of the system architecture function well with the applied set of data, especially after automating the process of extracting the LBS data from VICO Office. 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 complete. Furthermore, it is assumed that the developed solution can be applied to any big scale construction project with similar specifications as the selected case study project.

Secondly, the current solution also contains some limitations and issues that are identified in the case study or earlier in the process of prototyping. The following list is summarizing these findings which shall be considered in the further development of the solution.

- The current version of the solution only considers formwork as a representative of TCIs. To offer a holistic tool for planning and managing TCIs on a construction project, it should include several different TCI-types.
- The formwork-specific solution should also be extended to include the whole range of items that are used to construct in-situ walls (e.g. pouring platforms, safety rales)
- In addition to the previous point, the solution is currently also not able to consider the sequence of the formwork cycle as already mentioned in chapter 2, in which the simplifications are explained. If a wall has no corner, the ending must be closed with walers and plywood at the end of a wall sequence to prevent the concrete from pouring out. The plywood must have the height of the formwork, the width of the concrete thickness, and an approximate thickness of 2 cm. Then, tree walers shall be placed around the open wall ending to support the plywood and hold the concrete in place.

- The wall thickness of the walls for the case study is manually set to a default of 350 mm. This number is set statically in the demo project, as all walls had a thickness of 400 mm. In the case study, this number was then manually adjusted to 350 mm as 70% of the regarded in-situ walls have a thickness of 350 mm. Currently, the solution is not able to automatically adjust the formwork calculation to the thickness of the regarded wall. This does not influence the formwork calculation for straight walls. The calculation of formwork corner elements, however, is directly affected by the wall thickness as it determines how much length the corner takes up from the total wall length of a wall. As the walls in the case study have variating thicknesses of 350, 390, and 470 mm the calculation of the corner elements is slightly incorrect for some walls which do not have a thickness of 350 mm and contain a corner. Further development should enable the calculation engine of the solution to flexibly adjust the calculation of the corner elements, based on the wall thickness of the modelled wall.

- As already mentioned in chapter 2, the solution assumes that the modelled wall geometries are aligned with the construction process, meaning that a location manager in the location-based schedule will not cut a wall into two, because the wall is modelled too big and does not fit in the location system of the project. This limitation must be addressed in the early stages of a project to ensure that the model meets the requirements to use the proposed solution. An alternative to the early quality assurance of the model is that the contractor adjusts the model as the location-based schedule is created.

- The solution, moreover, does not consider walls with T-junction correctly as they are identified as corners and the solution consequently applies a corner element. The wall 12502993 in section 45.6 of the case project (see figure 22), for example, has two opening walls. Currently, only up to two wall connections per wall (on each ending) are supported by the developed prototype. Thus, further development of the solution has to also consider more complex wall connections.

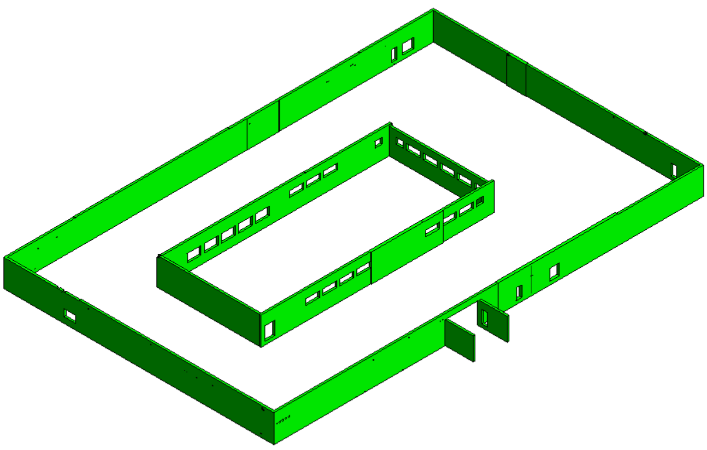


Figure 22: Orthogonal wall opening in the case project'

- The Linked Data remote controlling engine "comunica" would enable a more automated data management in the triple store, where the data of the solution is hosted. It shall be investigated why the engine is currently not working with the triple store of Jena Fuseki and further development shall automate the data management part of the solution.

- The second simplification of the prototype restricts the formwork calculation engine to only consider the formwork application in one dimension as it is assumed that the formwork elements are always higher than the wall elements. A two-dimensional consideration would not only improve the calculation for vertical formwork but also allows to apply the solution for calculating the formwork demand for horizontal concrete structures as concrete slabs. Furthermore, the algorithm to apply the formwork elements consecutively to the regarded wall can be improved. Currently, the algorithm is trying to place the least amount of formwork elements on the given wall geometry and is then applying a timber filling. In some cases, it might be more realistic to apply two smaller formwork panels if this results in a smaller or even no timber filling. Therefore, more advanced algorithms shall be utilized in the solution to improve the formwork calculation e.g. to include more wall connections, have a more efficient calculation, and a two-dimensional consideration.

- The developed solution aims to visualize the developed TCI utilization plan for both the construction workers and the management level and by that utilizes two visualization tools. Currently, only the dashboard is developed as a functioning solution, while the mobile application remains a concept. The next step of prototyping would be to develop the conceptual extension of the Execute mobile application to distribute the TCI utilization plan to the construction site and workers.

With this reflection on the findings of the case study, this documentation provides an objective view on the current status of the prototype solution and helps to classify and understand the level of development, the current prototype is in.

Chapter 5. Bibliography

Yin, R. K. (2014). *Case study research: Design and methods* (5. edition): Sage.

Appendix 5.1

Interview Guide for State-of-Art Report

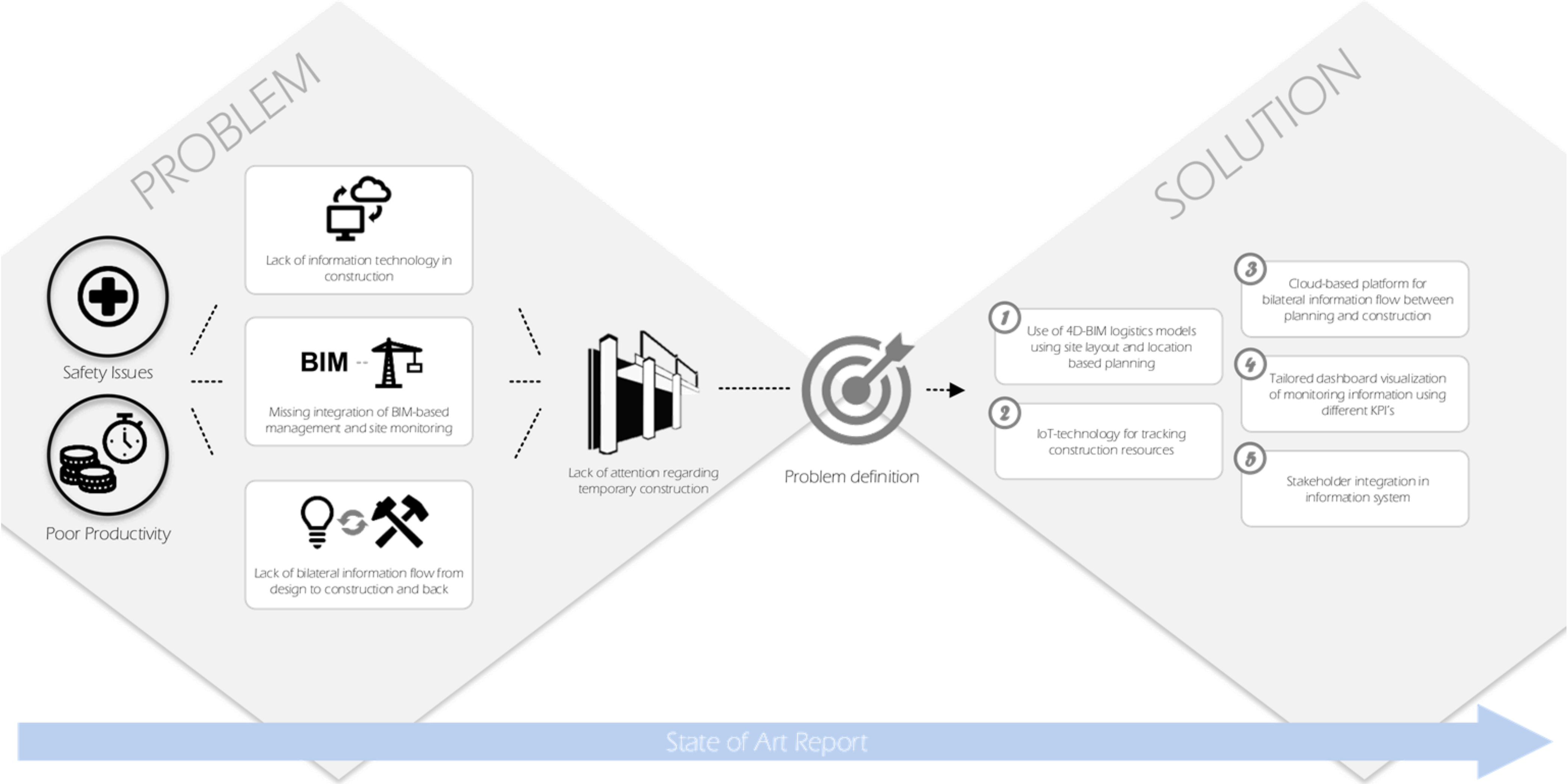
Integrative and lean logistic management process of temporary construction items

Interview for validating the state of art review & framing the research objective

Key Question: *How can performance issues in construction be resolved by integrating temporary construction items (TCIs) in the logistics and site management?*

State of Art Review framing the research objective

Problem and solution space derived from literature



Section 1: General

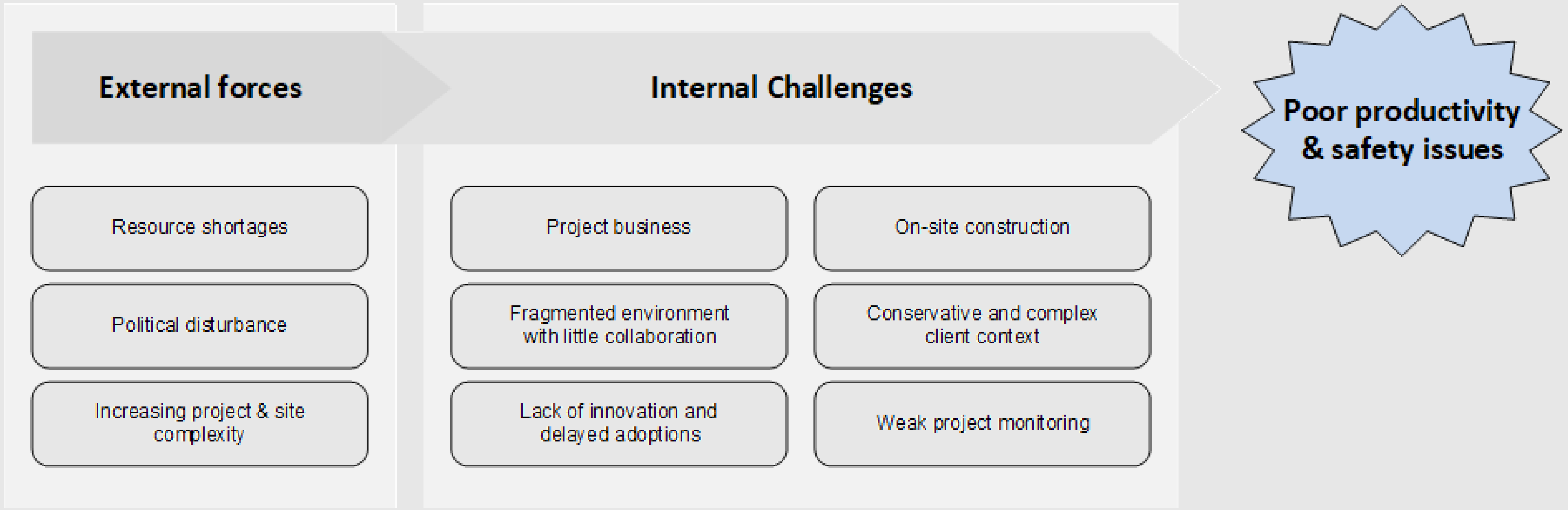
Question 1
Can you give a background about yourself and your career? What are your experiences with the use of technology in site & logistics management so far?

Section 2: Problem Space

Question 2

Assumption: In literature, poor productivity and safety issues are identified as common problems on construction sites, caused by elemental constraints and shortcomings in the industry (referring to the chart below).

Question: Do you agree on this and where (regarding site and logistics management) do you see the most potential to overcome these challenges?



Section 2: Problem Space

Question 3

Assumption: Missing integration of BIM and IT at the construction site is a big shortcoming of the industry, resulting in weak site monitoring and project management because of one-way information flow and lack of structured data?

Question: How can technology improve site logistics management and why is updated data from the construction site important?

DTU

Section 3: Problem Space

Question 4
Assumption: There is a lack of attention and information regarding **temporary construction items (TCIs)**. Temporary works is only included as an estimate or percentage of the total cost but is often not planned and monitored properly. Question: From your experience, how are temporary construction items managed and what would be the benefit of more and updated data about these items?

Section 3: Solution Space

Question 5

Assumption: Considering temporary construction items (TCIs) in construction planning can reduce waste, costs and safety hazards.
Question: How to integrate TCIs in construction management in a simple way? What type of temporary construction items (e.g. formwork, supporting struts and safety barriers)?

Section 3: Solution Space

Question 5 - Reference

	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 construction site	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
	Gates in fences	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
	Formwork	m2
	Supporting structures	stk
	Material container	mdr
	Smaller machines and hand tools	man hours
	Crew modules 10 men	months
	Office modules 2 rooms with toilet and tea kitchen	months
	Toilet box	months
	Office set furniture	months
	Cleaning sheds	stk*mdr
	Electrical installations rental excl. consumption	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 and crew modules	stk
	Disassembly of toilet boxes	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

Section 3: Solution Space

Question 6
Assumption: Five recommendations for developing a solution are derived from the state of art review. Question: Where do you see the most potential as a focusing area of the research? What should be the primary research objective?

Section 3: Solution Space

Question 7
Assumption: An IoT-based real-time tracking system is a further development in the management process improvement of TCIs. Question: How can temporary construction items be tracked? How should the tracked data be received, processed and then used to add value to the project?

Appendix 5.2

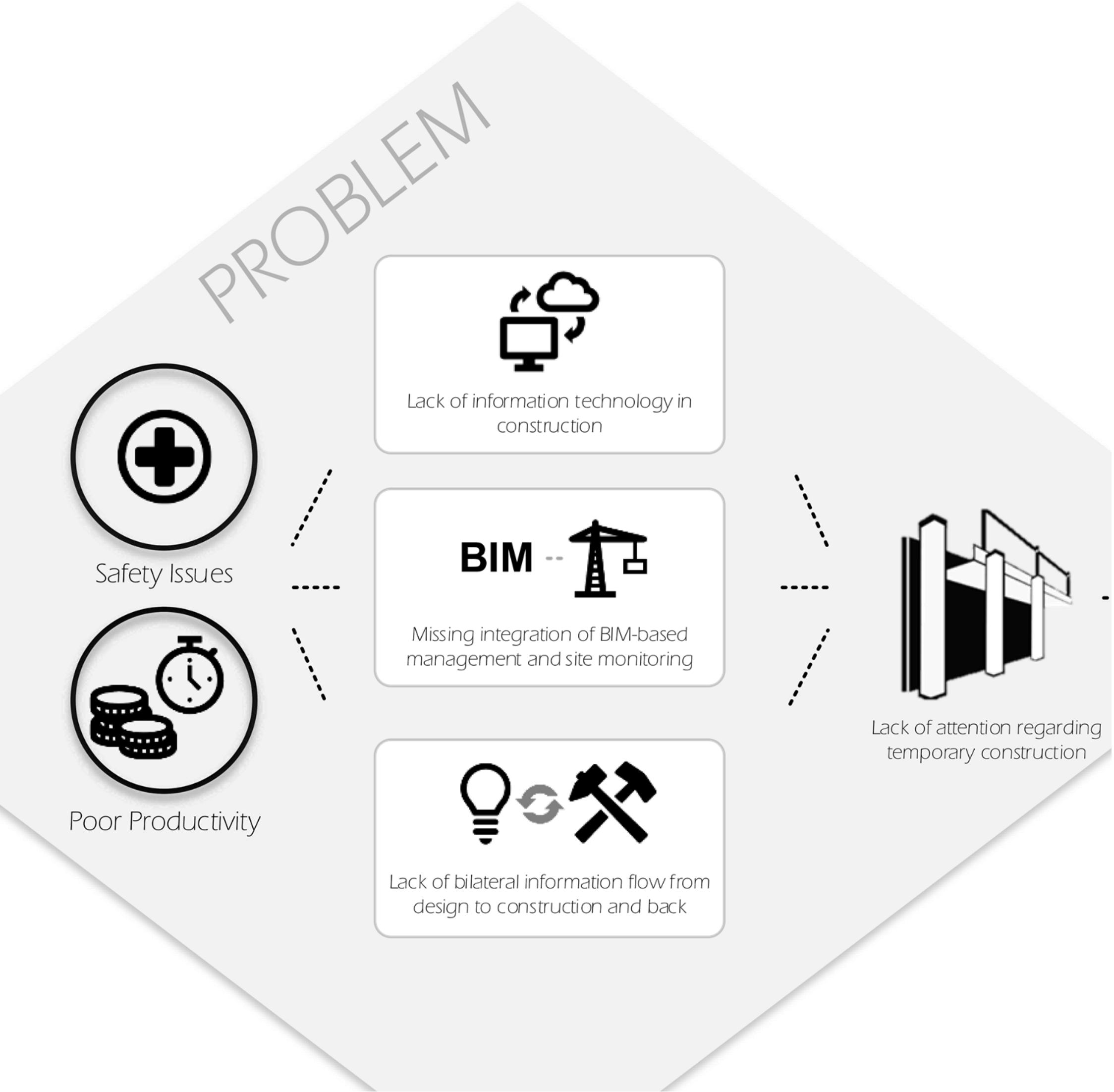
Interview Guide for Concept Development

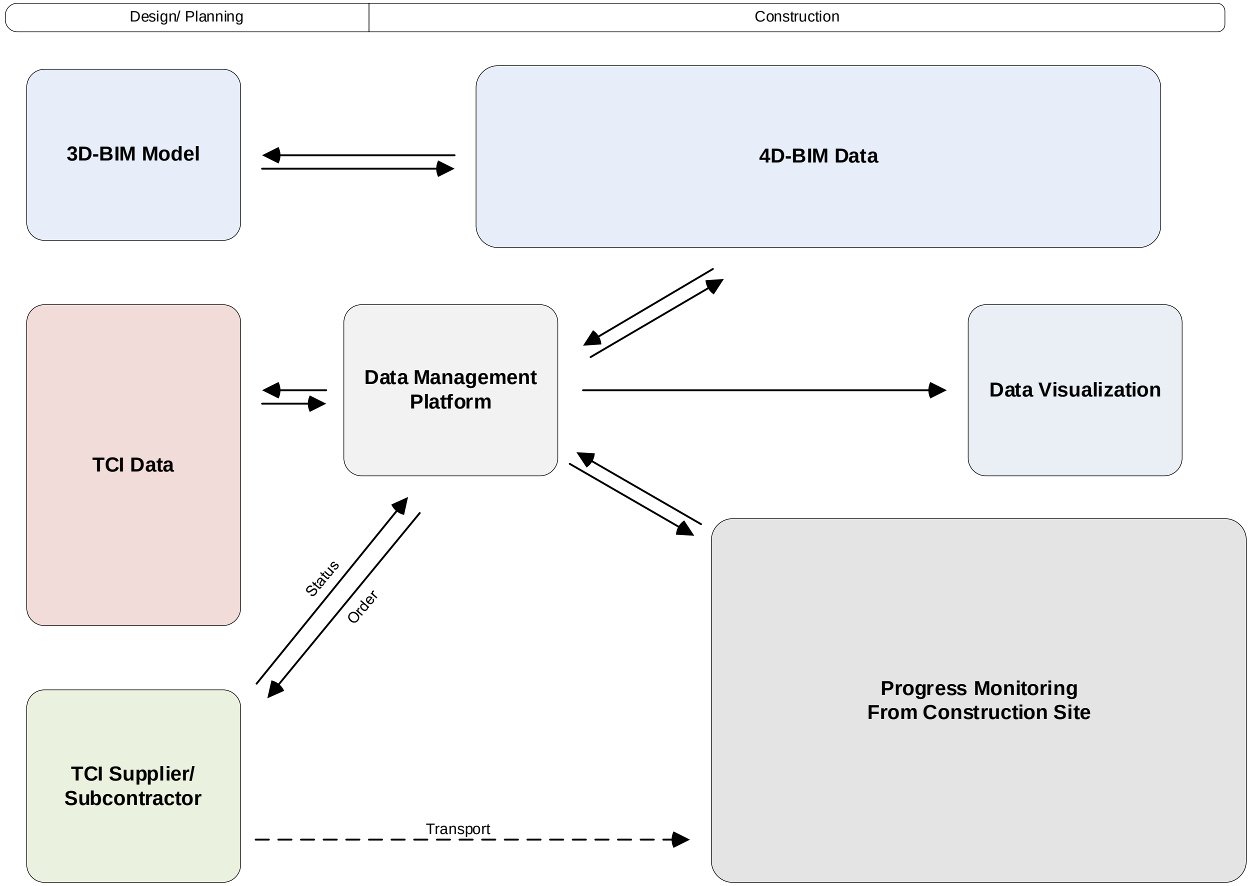
Integrative and lean logistic management process of temporary construction items

Interview for validating theory about temporary construction items (TCIs) and receiving new solutions from the industry.

Key Question: *How can productivity and safety issues in construction be resolved by integrating temporary construction items (TCIs) in the logistics and site management process?*

Improved management process of TCIs





Section 1: General

Question 0
Can you give a background about yourself and your career?

Section 1: General

Question 1
What products does your organization provide for construction sites? How's the future demand regarding these products expected?

Section 1: General

Question 2
How do you supply construction sites with your product and what services do you provide with your products? Do you use any technology to facilitate this process?

Section 2: Problem Space

Question 3

How are temporary construction items considered in a construction site regarding budgeting, management and monitoring?

BUDGETING	MANAGEMENT	MONITORING

Section 2: Problem Space

Question 4
Assumption: Items, such as formwork and supporting structures are used repeatedly during construction. These items produce waste and block construction progress because they are not properly considered in construction management. Question: What items create the most difficulties regarding site & logistics management on site? Where is the most potential to make improvements?

Section 3: Solution Space

Question 5
What data or information would be needed to improve the management of formwork? How can this information be obtained?

Section 3: Solution Space

Question 6
Assumption: By linking the TCIs to their related construction activity, it must be possible to derive amount and type of TCIs. Question: Is it possible to automatically generate the number of standard formwork based on geometry of building parts? Does your organization have such a solution?

Section 3: Solution Space

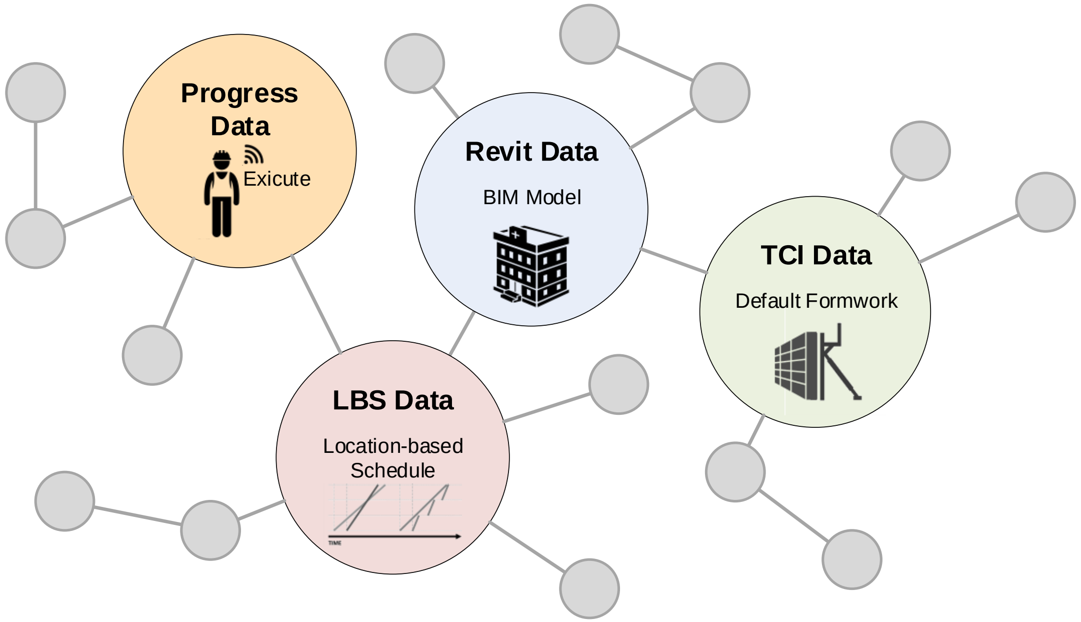
Question 7
Assumption: The proposed process improvement of site & logistics management regarding TCIs is proposed. Question: In your opinion, how will this setup improve productivity and safety on site? How would you as a supplier benefit from it?

Appendix 5.3

Interview Guide for Evaluation Interviews

Unlocking the value of Linked Building Data (LBD)

A Lean and integrated management process of temporary construction items (TCIs)



Interview for evaluating the developed prototype solution and its potential in the construction industry

Alexander Schlachter | s182781@student.dtu.dk

Interview Guide

I. Solution Presentation

II. Evaluation Interview

- Introduction of Interviewee — Section 1
- General Validation of the Solution — Section 2
- Improvements/ Further Development — Section 3
  - Data Sources & Extraction
  - Data Management
  - Data Processing & Querying
  - Data Visualization & Distribution
- Business Model — Section 4

Section 1: Introduction of Interviewee

Question 1
Can you give a background about yourself and your career? What are your experiences with the use of BIM-based technology in construction planning & management?

Section 2: General Validation of the Solution

Question 2
What is your first impression after the presentation of the prototype solution? From your perspective, where do you see the most potential in the proposed solution, integrating TCI planning and management in the existing BIM-based project delivery?

Section 2: General Validation of the Solution

Question 3

What are the benefits of the proposed solution? Can you name the benefits for each of the following stakeholder group? Who else might benefit?

Client	Contractor/ CM	TCI Provider

Section 2: General Validation of the Solution

Question 4
By integrating TCI planning and management into the construction process, the proposed solution aims to improve productivity and safety on site. In what extent do you see this intention fulfilled? What would be required to solve both issues with the proposed solution?

Section 3: Improvements/ Further Development

Question 5
Would you and how would you use the proposed solution in one of your projects? What further development/ considerations are needed to apply the solution in a real construction project?

Section 3: Improvements/ Further Development

Question 6
Step 1 - Data Sources & Extraction: Do you see any obstacles in the way, the BIM-data is now extracted from a project? What modifications are needed to apply this step in a real construction project?

Section 3: Improvements/ Further Development

Question 7
Step 2 - Data Management: Do you see any obstacles in the way, the data from different sources is now stored & managed as Linked Data in a triple store? What are the requirements for a Linked Data environment for a project?

Section 3: Improvements/ Further Development

Question 8
Step 3 - Data Processing & Querying: Do you see any obstacles in the way, the data is used to provide all needed information to create a TCI utilization plan? What modifications are needed to apply this step in a real construction project?

Section 3: Improvements/ Further Development

Question 9
Step 4 - Data Visualization & Distribution: How can the developed TCI utilization data be visualized to create value on a construction site? The proposed solution allows to display the data both in a linked Power BI-Dashboard as well as the application Exicute. Is this approach reaching all parties in a construction project who can benefit from the developed data?

Section 3: Improvements/ Further Development

Question 10
The proposed solution is enabling a passive monitoring of TCIs, based on progress information from the construction process. A further development for an active tracking of TCIs is the implementation of IoT-sensors. What is your opinion about this? Is an active tracking necessary for TCIs on a construction site? If yes, how can this technology be implemented in the system architecture?

Section 3: Improvements/ Further Development

Question 11
Is the prototype solution easily adjustable to create a holistic TCI planning & management tool, not only for formwork but also for other TCIs as scaffolding, supporting structures or fencing? Where do you see obstacles in that?

Section 4: Business Model

Question 12
The ideal future scenario (presentation slide 42) requires an involvement of many different stakeholders in a construction project, to deliver their specific input as linked open data, which will be accessed by a calculation tool. Is this vision realistic in the near future? Why?

Section 4: Business Model

Question 13

Assuming that the proposed solution is offered as a **Consultancy Service**, providing detailed information about the TCI utilization on a construction site. What would be the benefits of this business model? Would you consider paying for this service?

Section 4: Business Model

Question 14
Assuming that the proposed solution is developed as a **holistic Software Solution**, providing detailed information about the TCI utilization on a construction site. What would be the required further developments of the existing prototype and potential obstacles? What are the benefits of this business model? Would you consider buying this software?

Appendix 5.4

Interviewee Introduction

Interviewee Introduction			
No.	**Name**	**Company**	**Group**
Interviewees for Chapter 2 (State of Art Review)			
1	Client Advisor	Exigo A/S	Consultancy
	- Bachelor degree in structural engineering - Master degree in construction & management - Project Manager at Exigo with main project SDU in Odense - Responsible for the successful implementation of Exicute in construction projects - Denmark has an innovation advantage compared to the US and other countries as it implements technologies early - Don't use this technology regarding the site and logistics. Data is taken and transferred manually which is time consuming and error prone		
2	Head of Digitalization	Consultancy A	Consultancy
	- Bachelor degree in Civil Engineering - Master degree in software development and industrial - PhD in design management - 15 years of experience in transforming the construction industry, by implementing digital technology on construction projects that creates value - Work with BIM and digitalization in his professional career for different contractor and consultancies - 4D-Models and use of VICO to improve construction - Focus on productivity enhancing tools for construction a) How to report back from site --> Progress monitoring b) Image recognition for safety and productivity improvement --> analyze pictures to see progress based on model - Now at Consultancy A: Enabling companies that wants to enhance its profile in digitalization of the construction industry		
Interviewees for Chapter 5.1 (Improving the TCI management process)			
1	Head of Department BPI (Construction Site Layout)	TCI Provider A	TCI Provider
	- Head of department BPI Construction site layout at TCI Provider A (5 years) - 25 years experience in logistics management in general - 14 years experience in logistics management of building materials in construction - Experience in logistics management in construction - Expert in construction site layout planning & management - Knowledge about the management of TCIs - Implementation of technology in construction site supply & management		
2	BIM Specialist	TCI Provider B	TCI Provider
	- More than 2 years as BIM Manager in TCI Provider B - Department of Digital Transformation - BIM Competence centre at TCI Provider B - Bachelor degree in Construction Project Management - Currently studying a master degree in Energy Efficient Design - Experience in BIM process integration for TCIs in construction projects - Provides TCI product information for prototyping		
1	Supervision Leader & Construction Manager on client side	Client A	Client
	- Construction Management/ Supervision from the owner side - Responsible for case study project SDU SUND new university building (300 million DKK and 50.000 m²) Supervision Leader: - Profound experience for many years in construction and logistics management on site - Direct contact to case study project Construction Manager: - Structural engineer graduated in 2017 - Part of SDU SUND project for Client A		
Evaluation Interviews for Chapter 6			
1	Technical Manager, BIM Responsible & Design Engineer	TCI Provider B	TCI Provider
	Technical Manager: - Civil Engineer at TCI Provider B for 10 years --> Formwork planning and management - Former work experience as a contractor for 11 years --> Knowledge about construction site planning BIM Responsible: - BIM responsible for TCI Provider B since 1 year --> Formwork planning and management with BIM perspective - BIM experience based on sales aspect --> Not yet fully implemented at TCI Provider B as clients are not willing to pay for BIM as a service Design Engineer: - Construction Architect education - 7 years at TCI Provider B as a design engineer - Project engineer of SDU SUND (case study) --> Only delivered formwork elements without planning them --> Planning is on Contractor B		
1	Head of VDC	Contractor A	Contractor
	- VDC Development Manager - 2002: Career start as a technical drafter in Tekla - 2007: BIM specialist at a construction consultancy(Tekla expert with responsibility to develop templates and educate the staff) - 2013: BIM lead at a construction consultancy - 2016: Joined Contractor A as VDC Group Manager and later head of VDC - BIM experience mainly for planning and modelling reinforcement of concrete structures in 3D and using the result as quantities for the site workers		

Interviewee Introduction

No.	Name	Company	Group
2	Head of VDC & VDC Manager	Contractor B	Contractor
	Head of VDC: - Senior Technical Director, VDC Planning & Support - 28 years of experience as a BIM/VDC specialist and leader in a construction company - Supports student project as master theses and PhD dissertations VDC Manager: - VDC Manager at a construction company since 4 years - Bachelor and Master education in Architectural Engineering		
3	Lead VDC Manager	Contractor C	Contractor
	- Lead manager VDC at Contractor C - Master education in Building Informatics - Total of 10 years experience with BIM-based technology - 4 years experience as VDC specialist and leader in a big construction company - 7 year experience as a project leader - Schedule Planning, VDC, digitalization & ICT-Management - Advanced knowledge about the early stages in design, as well as from construction - Sees the main issue in the construction industry in the lack of collaboration between the design and construction parties		
4	Head of Department	Contractor D	Contractor
	- Education as a Construction Architect (graduation in 2005) - 14 years experience as a construction consultant, project manager and head of production - Knowledge and experience in both data driven construction and the challenges of implementing new technologies in construction - Experienced in BIM technology, location-based scheduling, data-driven information flow - Is using the exicute platform for construction projects		
3	CEO, Founder of Exigo A/S, Digital Construction Expert	Exigo A/S	Consultancy
	- Master degree in Civil Engineering as well as IT Engineering - PhD in IT in Construction - Part time associate professor for 10 years - 8 years experience in a big consultancy - Founded Exigo A/S 10 years ago and established the company as a leading Danish specialist in the integration of BIM with project and risk management		
4	Digital Development Director & Digital Engineering Lead Specialist	Consultancy B	Consultancy
	Digital Development Director - Master Degree in Civil Engineering - PhD in Design and Information Management in Construction - 12 years experience as an engineer as well as chief consultant in a big consultancy - Section Manager, VDC Business Development at a contractor for over two years - Digital development Director at Consultancy B mainly for buildings department since one year Digital Engineering Lead Specialist - 9 years experience at a construction company - 12 years now at Consultancy B, working as a BIM/VDC lead specialist		
5	Expertise Director ICT, Head of BIM & Linked Building Data expert	Consultancy C (NIRAS)	Consultancy
	Expertise Director ICT - over 30 years of experience in the industry as a project director and ICT expert - expertise area in ICT, BIM, process development and project planning regarding construction projects Head of BIM - 11 years of experience as a BIM specialist and leader - expertise in BIM and VDC, Data management, ICT, Location Based Scheduling Linked Building Data expert: - PhD in Linked Building Data - 7 years of experience as a HVAC engineer with focus on the implementation of Linked Data for different applications		
6	Senior Consultant	Consultancy D (Dalux)	Consultancy
	- originally started career as a carpenter - 5 years of experience as a architect on the main contractor side - Since 15 years expert into IT related to construction --> 5D planning and simulating the construction process --> Implementation of digital solutions in the construction industry --> BIM, usability, mobility and especially handover of data from Build to FM		
7	Head of BIM	Consultancy E (Rambøll)	Consultancy
	- M.Sc. in Structural Engineering - Working at Consultancy E since 20 years - Since 5 years responsible for the use of BIM in the buildings department - Experience in structural calculation, 3D-integration, BIM, Tekla Structures - Main perspective from consultancy but was also involved in sequence planning of construction workflows with VDC and site supervisions of big building projects		

Appendix 5.5

Solution Presentation for Evaluation Interviews

Lean and integrated management process of temporary construction items (TCIs)

Alex Schlachter
MSc. Architectural Engineering, DTU

exigo

Agenda

I. Problem & Solution Space

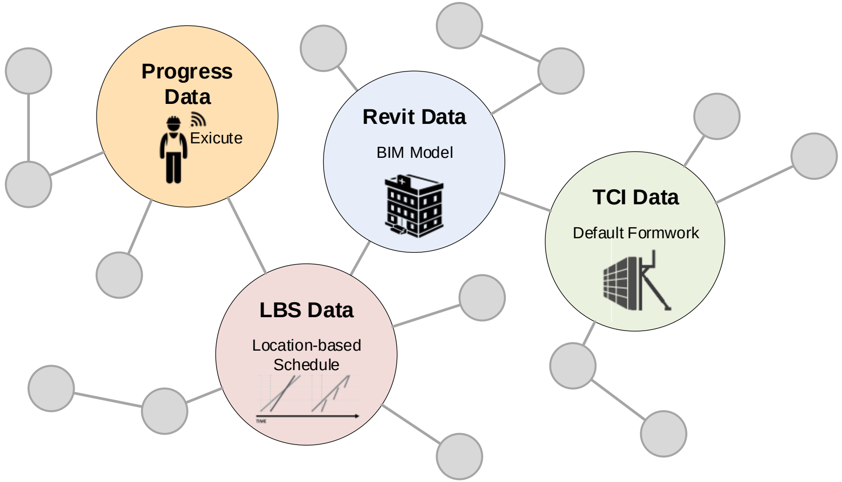
II. Proposed specific Solution

III. Linked Data in Construction

IV. Prototyping/ Demo Project
- Data Sources & Extraction
- Data Management
- Data Processing & Querying
- Data Visualization & Distribution

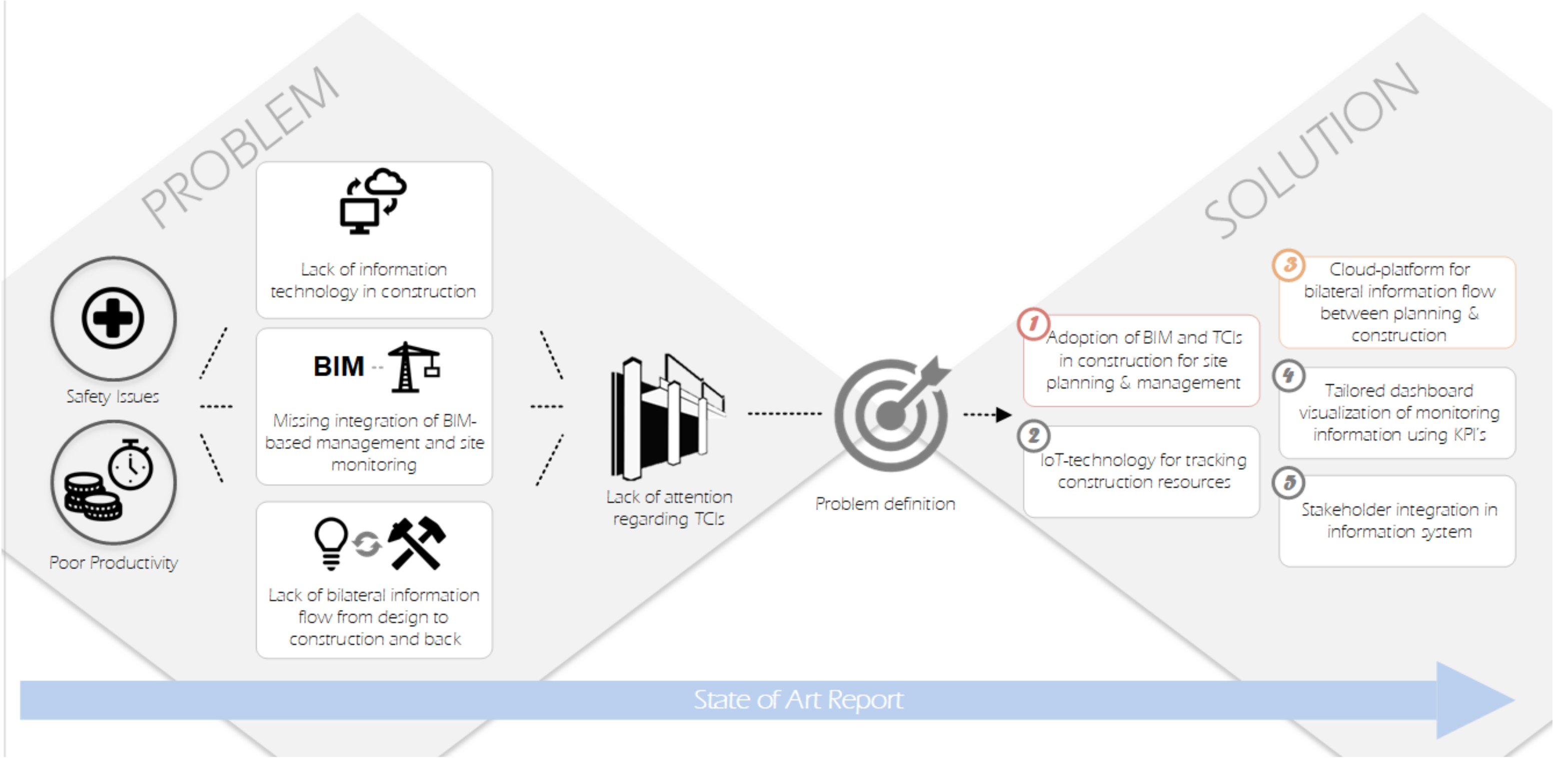
V. Case Study

VI. Ideal Future Scenario



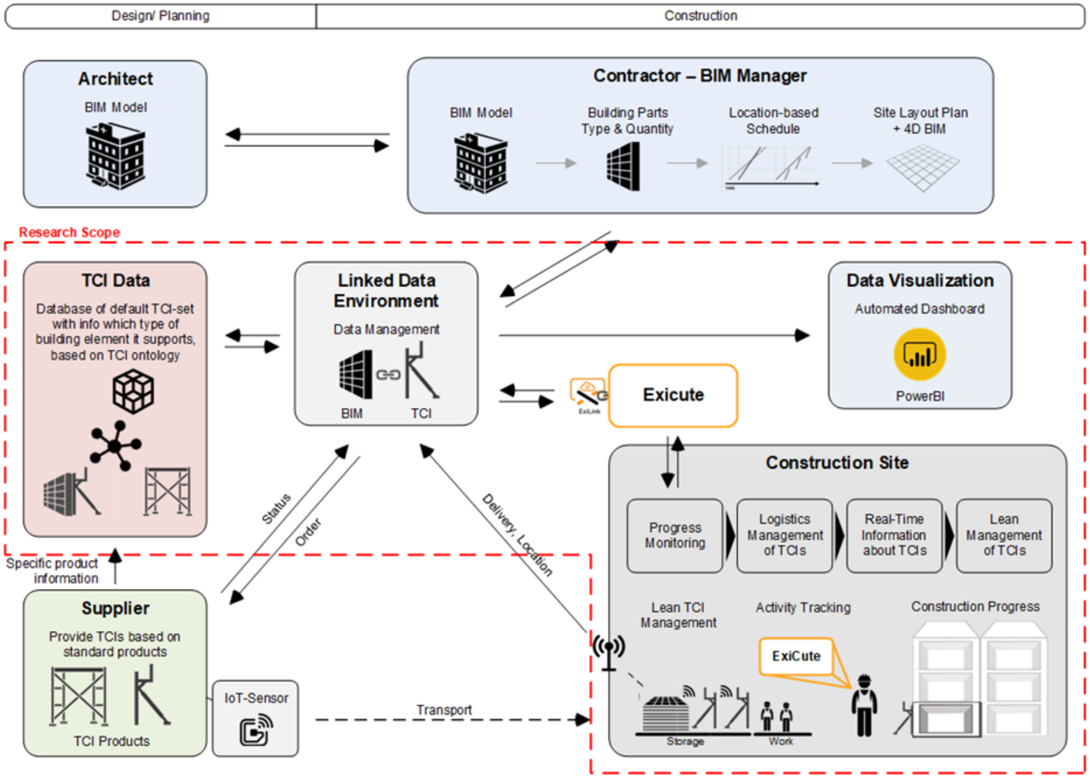
I. Problem & Solution Space

State of Art - Problem & Solution Space



II. Proposed specific Solution

Proposed Solution



Benefits

- Automatic planning of TCIs
- Goal to generate a TCI utilization plan
- Direct link of TCIs to permanents building elements supporting their construction
- Passive scheduling and monitoring of TCIs
- No additional planning effort
- Lean management of TCIs possible due to precise and updated data about TCI-utilization
- Possible extension with supplier software, product catalogues and IoT-tracking

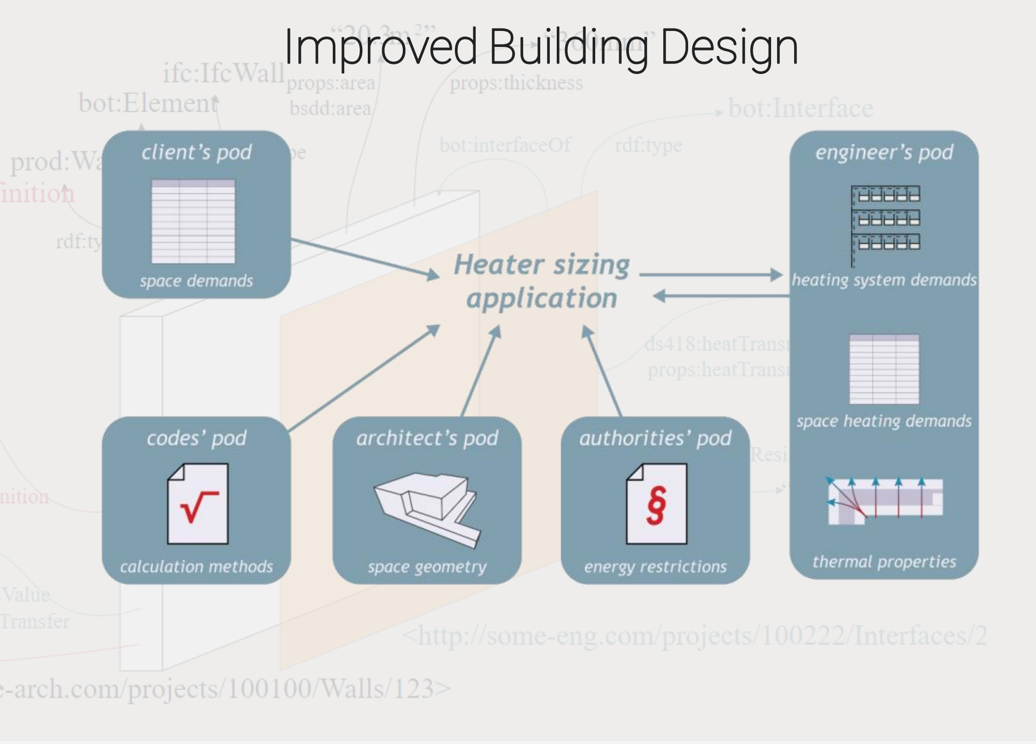
III. Linked Data in Construction

Linked Building Data (LBD) - Example

Data is stored and hosted by the stakeholder who generated it and is responsible for it

Data can be shared with authenticated people or be made publicly available

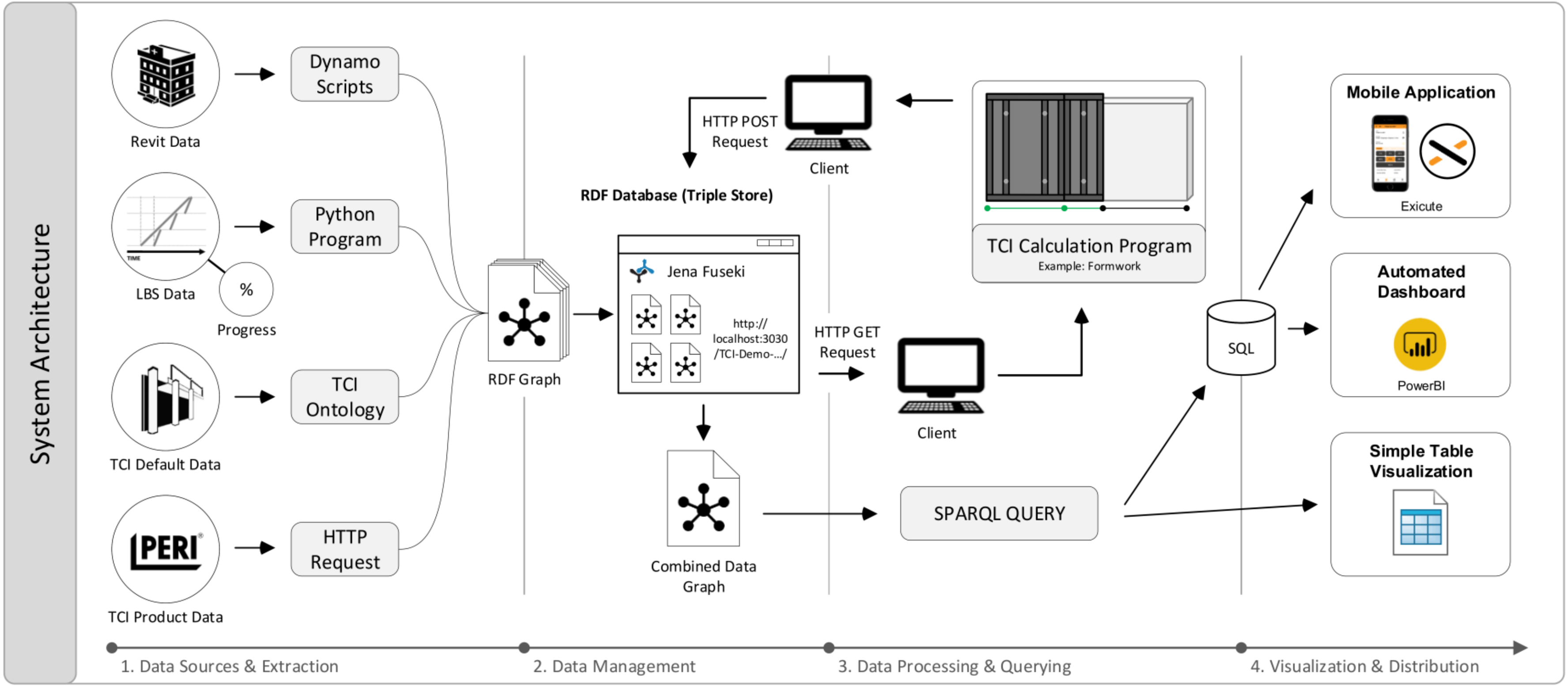
The model data can be extended with Linked Open Data (products, material properties, IoT, GIS)



Source: http://www.student.dtu.dk/~mhoras/presentations/20200305_bSNorway.html#/10/8

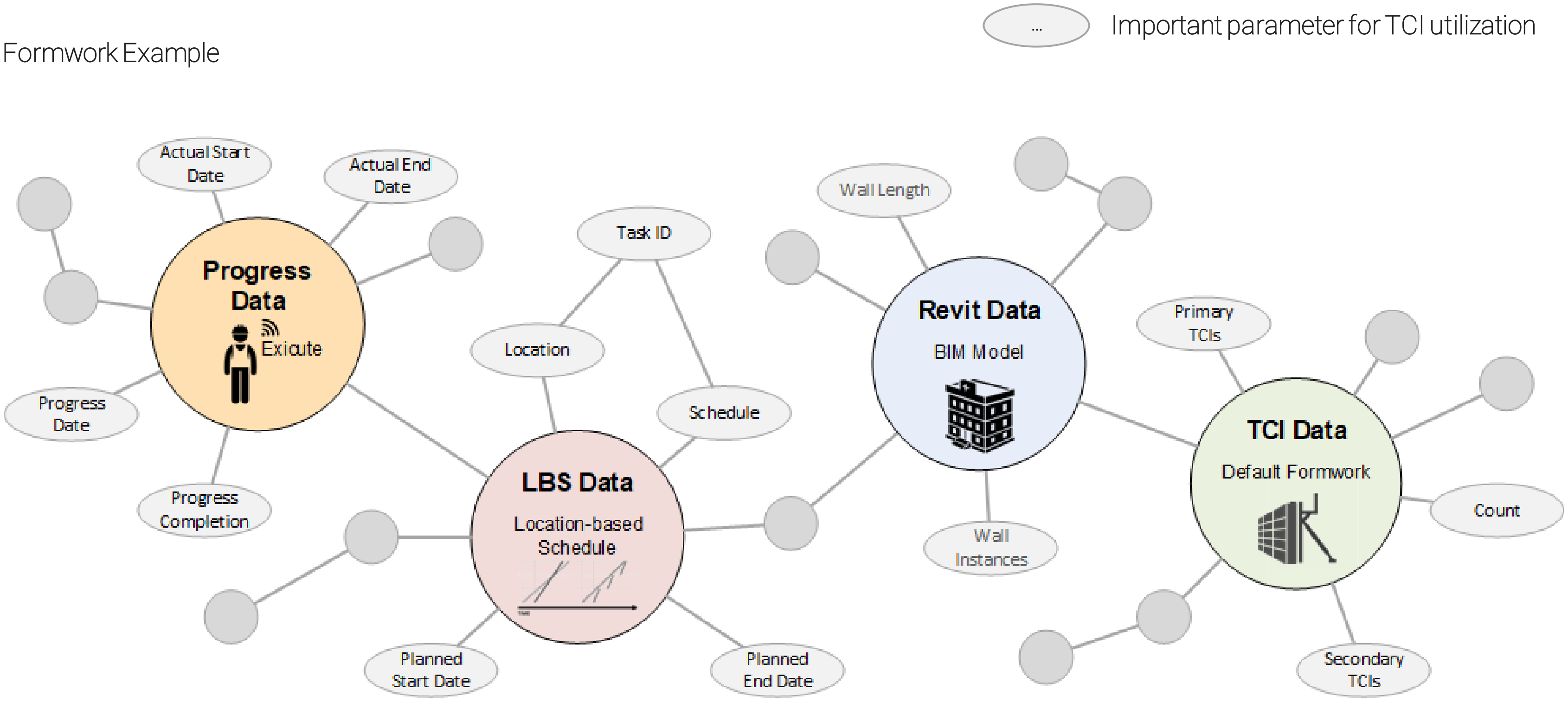
IV. Prototyping/ Demo Project

System Architecture



Data Sources

Formwork Example

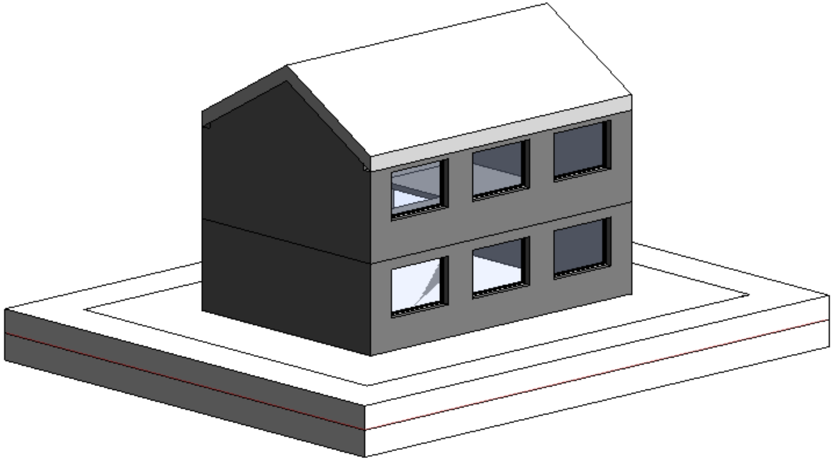


Building Model - **Revit**

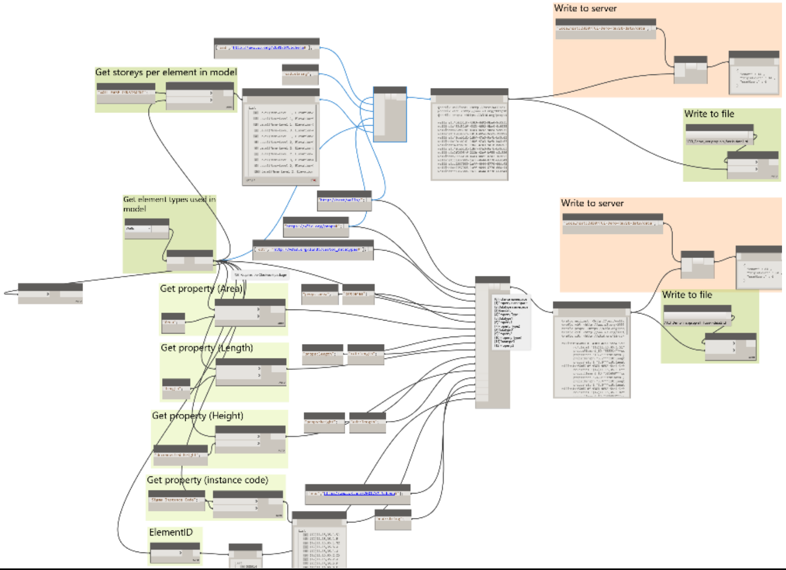
Revit Data

BIM Model

Data Generation in Revit



Data Extraction in Dynamo



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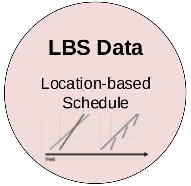
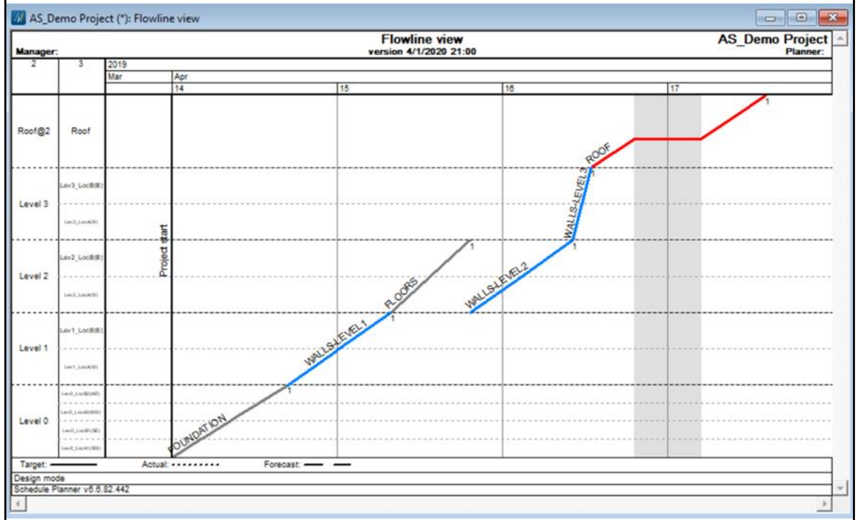
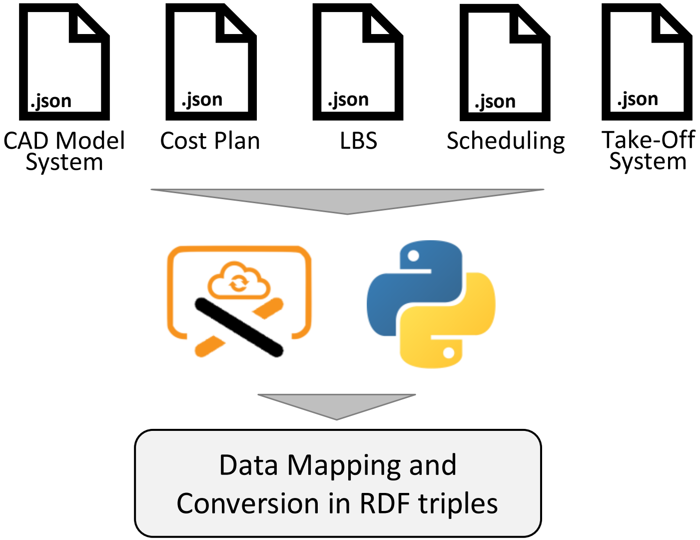
Location-Based Schedule – **VICO Office**



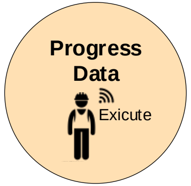
Data Generation in VICO

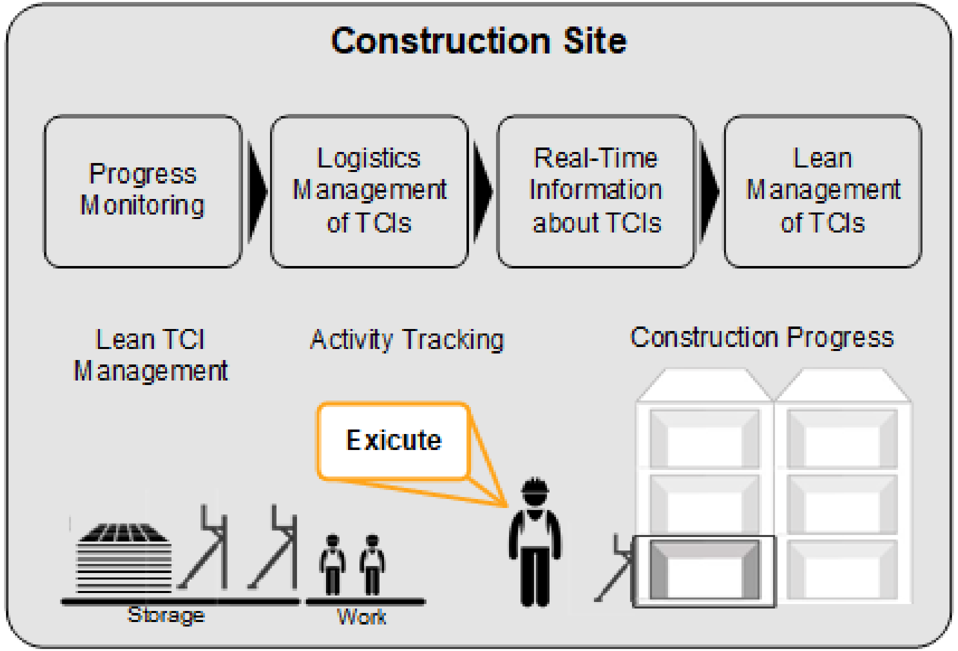


Data Extraction in ExiLink/ Program



Progress Monitoring – **Exicute**



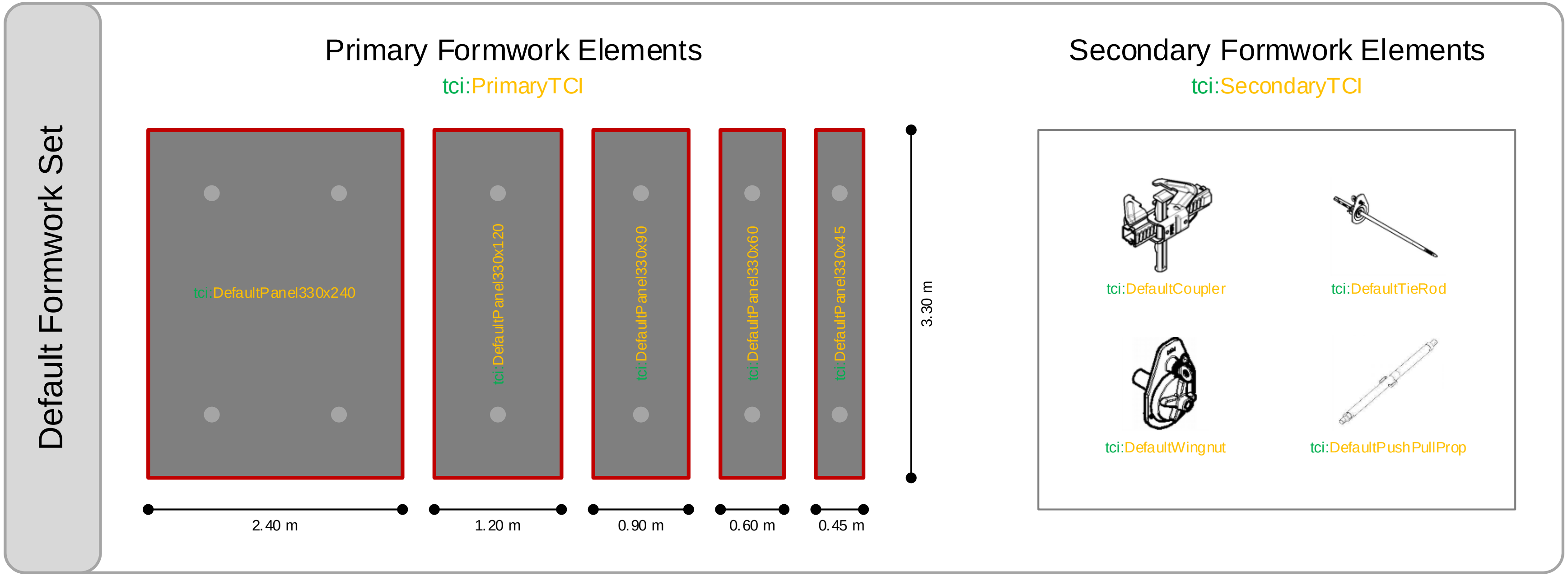


Temporary Construction Items – **TCI**

TCI Data

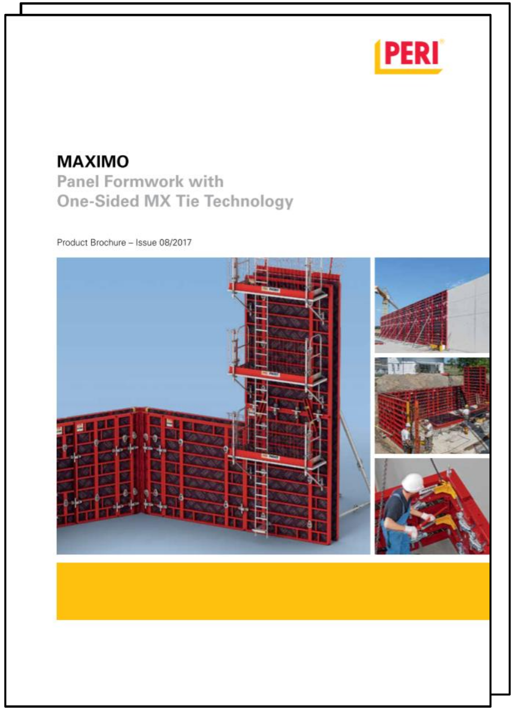
Default Formwork

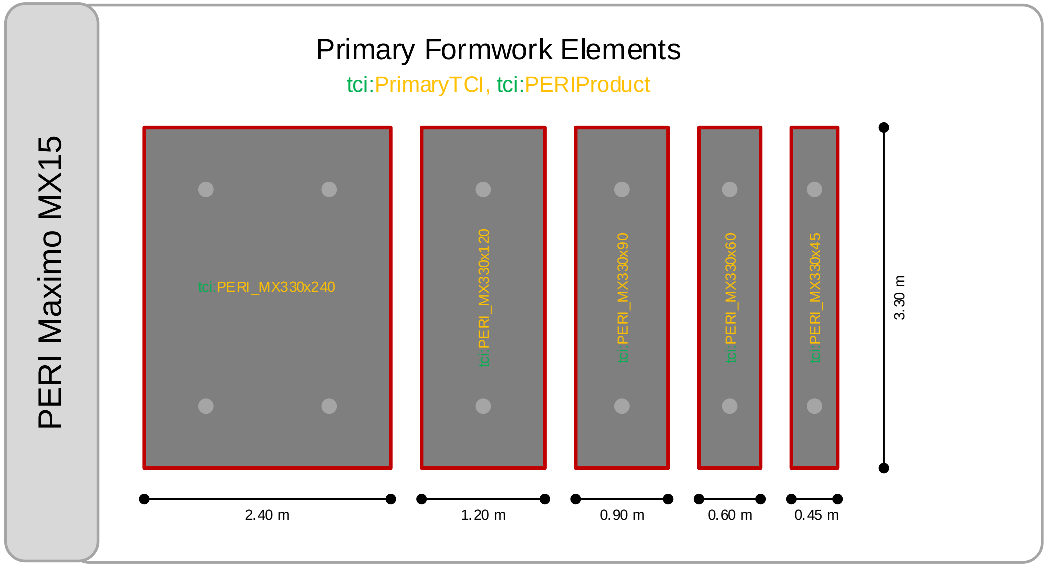
- TCI Ontology Creation describing the TCI context



Specific Product – **PERI MAXIMO MX15**

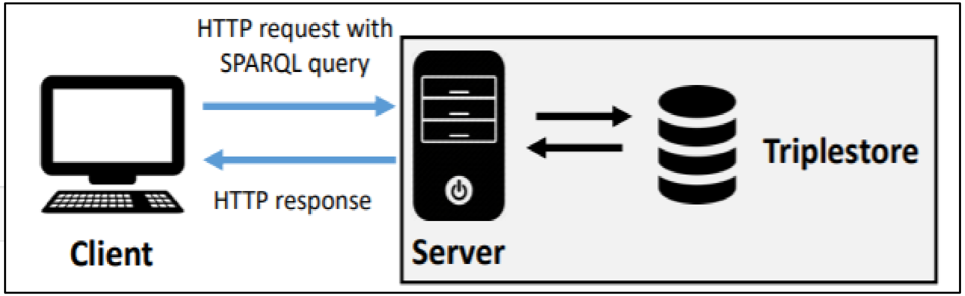
- Product Catalogue

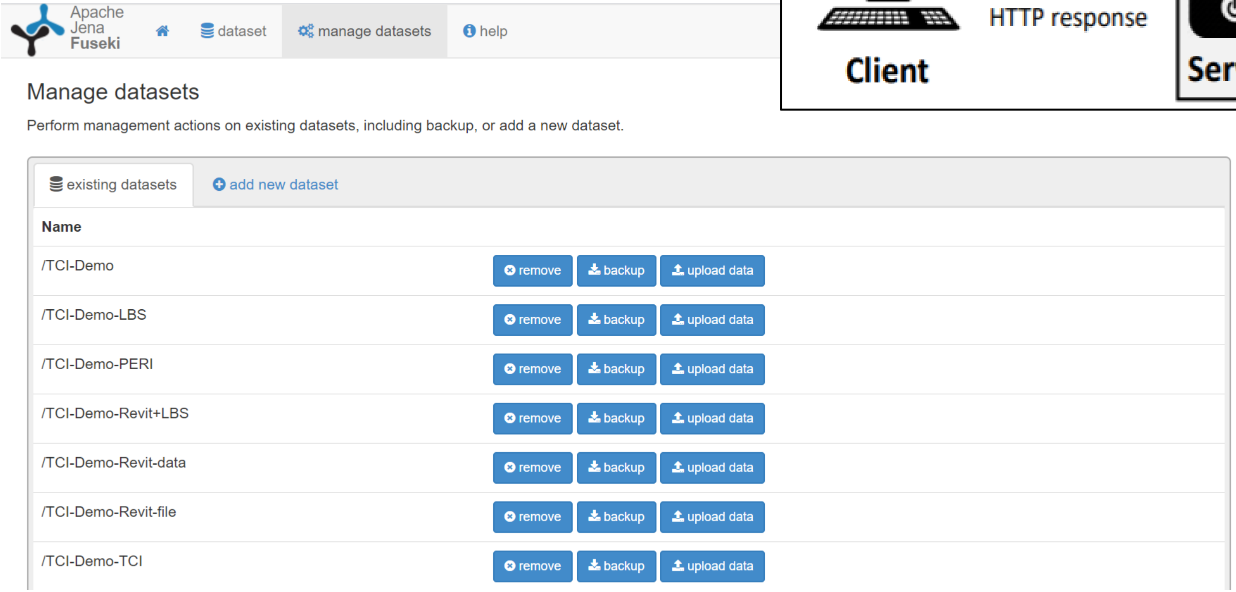




Data Management

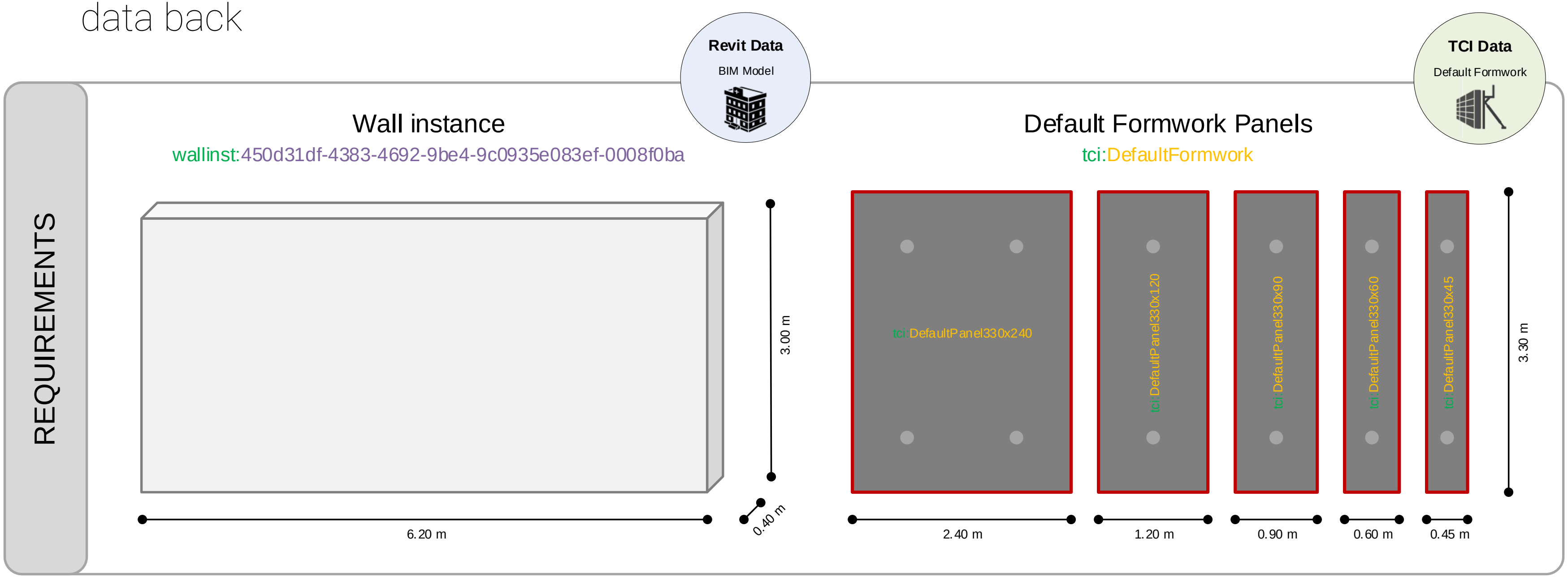
- Storage in triple store Jena Fuseki
- Access through localhost:3030





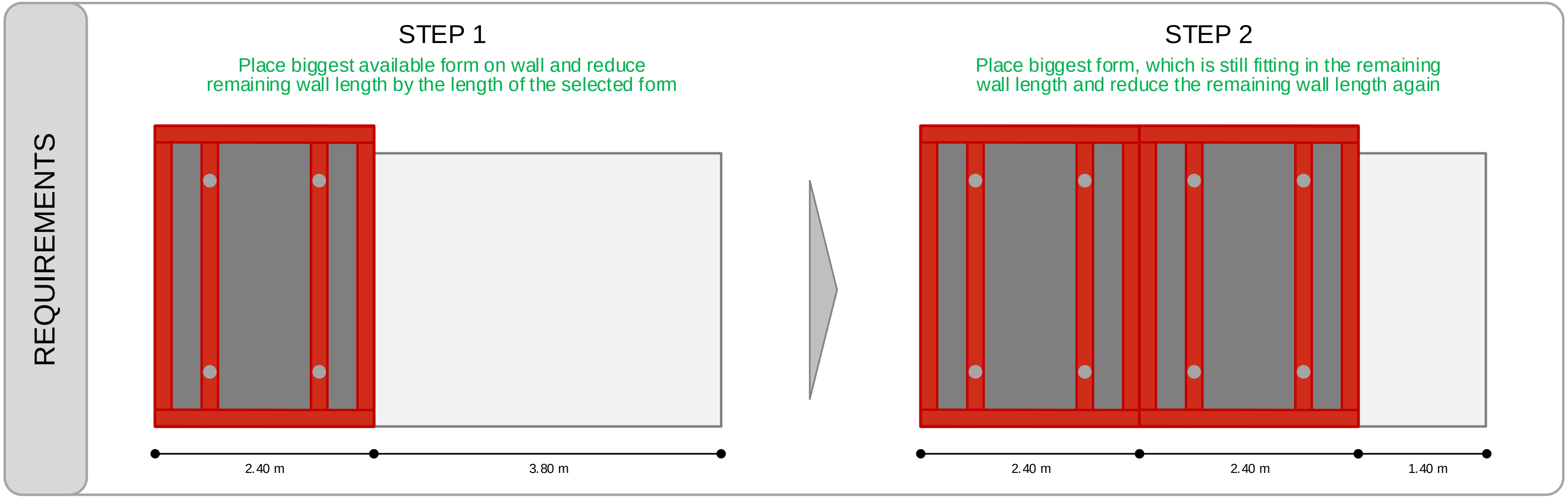
Data Processing & Querying

- Demo project for the calculation of formwork layout on wall elements
- Formwork calculation program that receives data from triple store and write processed data back



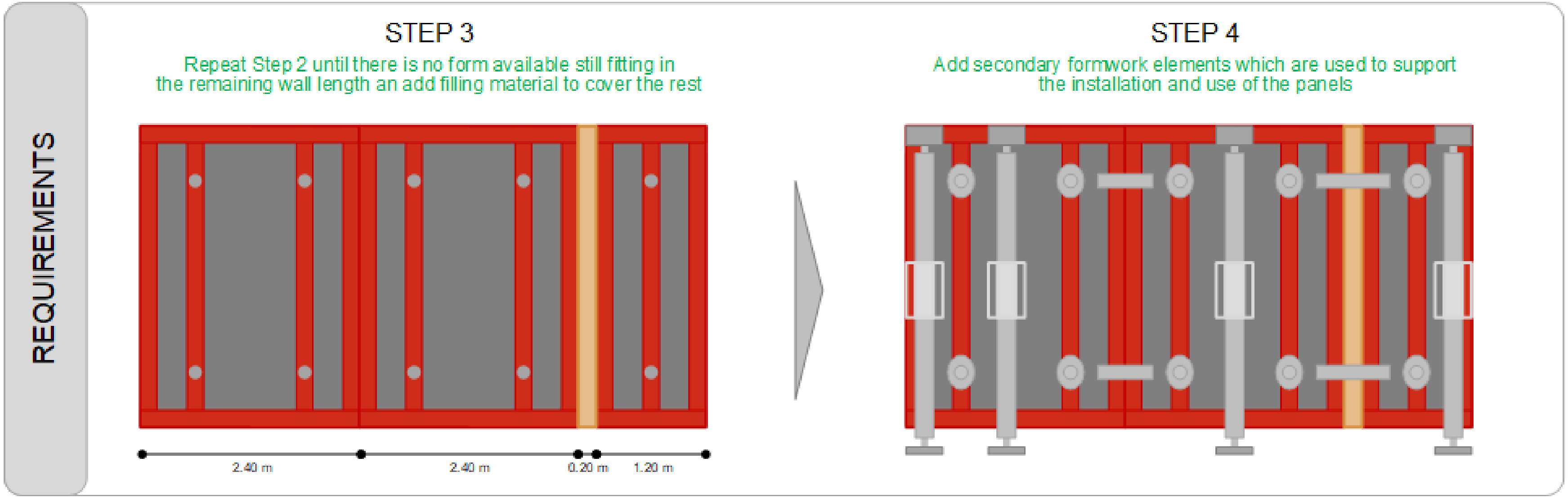
Data Processing & Querying

- Logic of Formwork Calculation Program



Data Processing & Querying

- Logic of Formwork Calculation Program



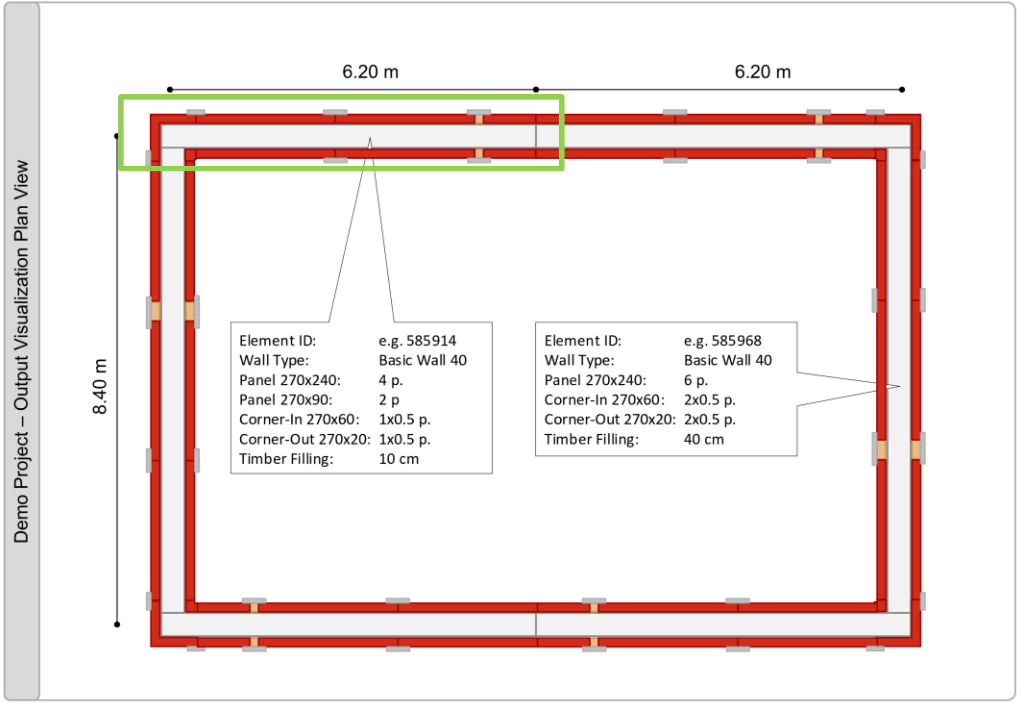
Data Processing & Querying

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						

exigo

Data Processing & Querying

- Demo Project - Output Data



ElementID	VICOinst	TCIs	Quantity
585914	1000.0.351404	DefaultCoupler	8
585914	1000.0.351404	DefaultOutsideCorner330x60	0
585914	1000.0.351404	DefaultPanel330x240	4
585914	1000.0.351404	DefaultPanel330x90	2
585914	1000.0.351404	DefaultPushPullProp	8
585914	1000.0.351404	DefaultTieRod	10
585914	1000.0.351404	DefaultWingnut	10
585914	1000.0.351404	TimberFilling	2
585968	1000.0.351451	DefaultInsideCorner330x20	1
585968	1000.0.351451	DefaultPanel330x120	0
585968	1000.0.351451	DefaultPanel330x45	0
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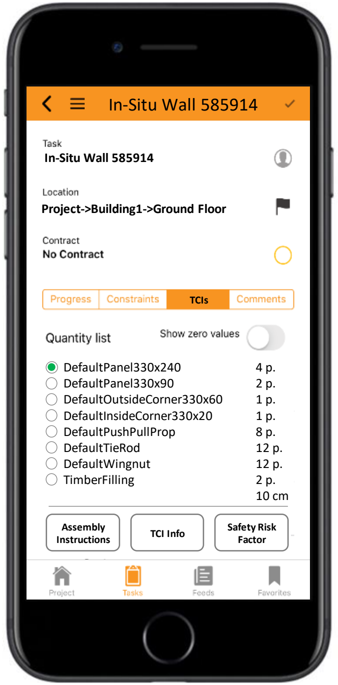
585968	1000.0.351451	DefaultPanel330x90	0
585968	1000.0.351451	DefaultWaler	0
585968	1000.0.351451	DefaultCoupler	12
585968	1000.0.351451	DefaultOutsideCorner330x60	1
585968	1000.0.351451	DefaultPanel330x240	6
585968	1000.0.351451	DefaultPushPullProp	10
585968	1000.0.351451	DefaultTieRod	14
585968	1000.0.351451	DefaultWingnut	14
585968	1000.0.351451	TimberFilling	2

Data Visualization & Distribution

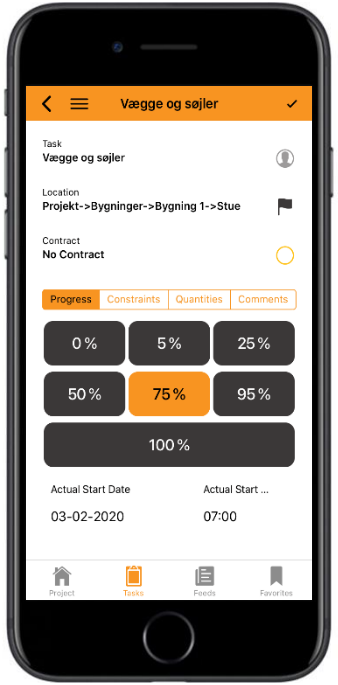
Information for Project Manager

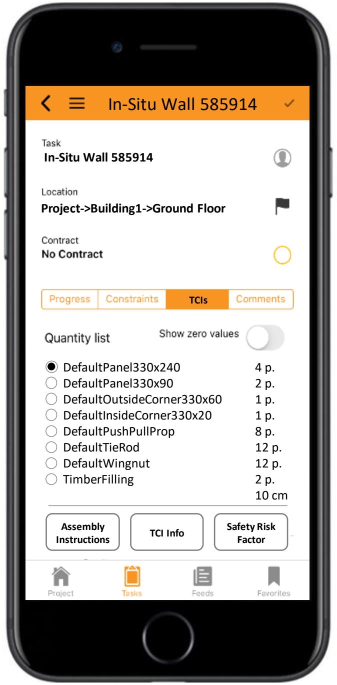
Information for Construction Worker



Data Visualization & Distribution

Option 1: Exicute Cloud Platform



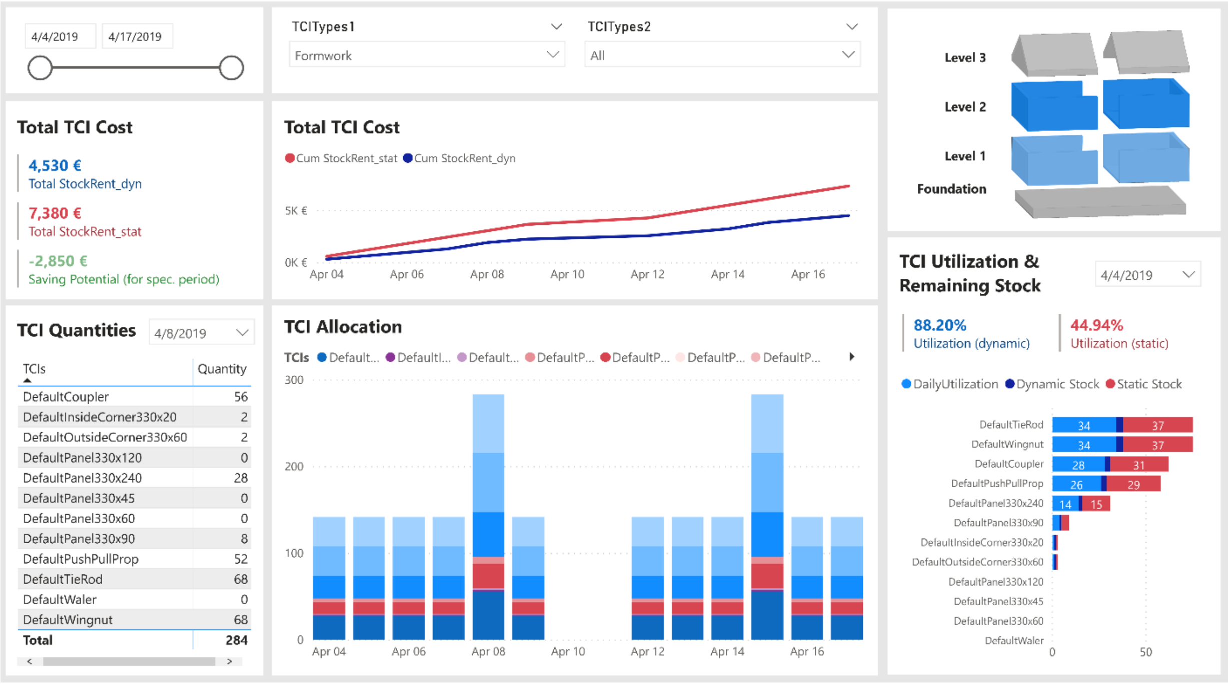


Integration in existing App

- Implementation of the proposed solution in practice
- Extension of the existing application "Ëxicute"
- New tab "TCI Quantities"
  - TCI quantities per task
  - Parameters of TCIs (weight etc.)
  - Installation time
  - Storage location before and after use
  - Safety Risk Factor
- Conversion of output data into SQL format in order to implement it in Exicute
- Could be an additional feature that can be sold to contractors

Data Visualization & Distribution

Option 2: Power BI Dashboard Visualization



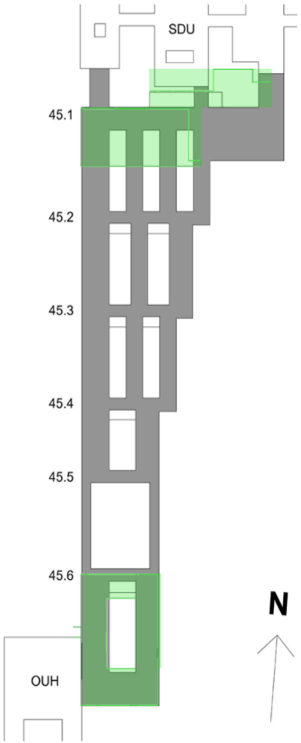
Automated Dashboards

- Direct link between triple store and Power BI
- TCI utilization plan over time
- Utilization of exploded model view to locate tasks
- Quantities & Types for upcoming tasks
- Current stock on site
- Etc.

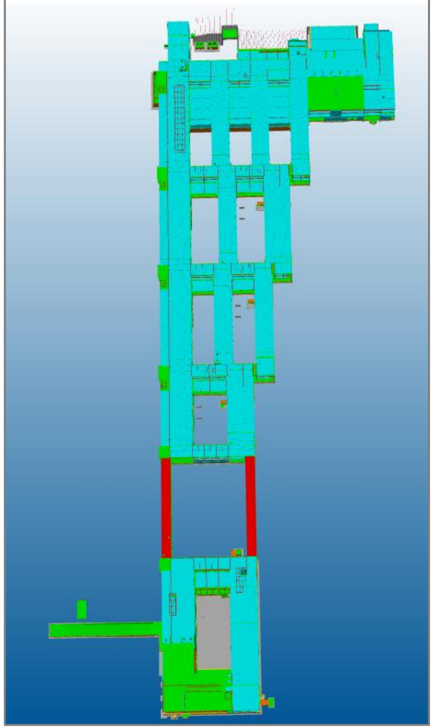
V. Case Study

Case Study – Project Information

Project Name	SDU SUND
Location	Odense
Project Type	Public, New Construction, Rural
Building Type	Healthcare Science Faculty
Building Size	50.740 m² brutto
Levels	Basement, Level 1-4
Building Sections	45.1 – 45.6
Value for Case Study	In-situ concrete walls are installed in the basement and serve as an application field for the developed prototype solution, creating a utilization plan for the required formwork
Used Data	• 3D-model (rvt-file) • Location-based schedule (vico-file)

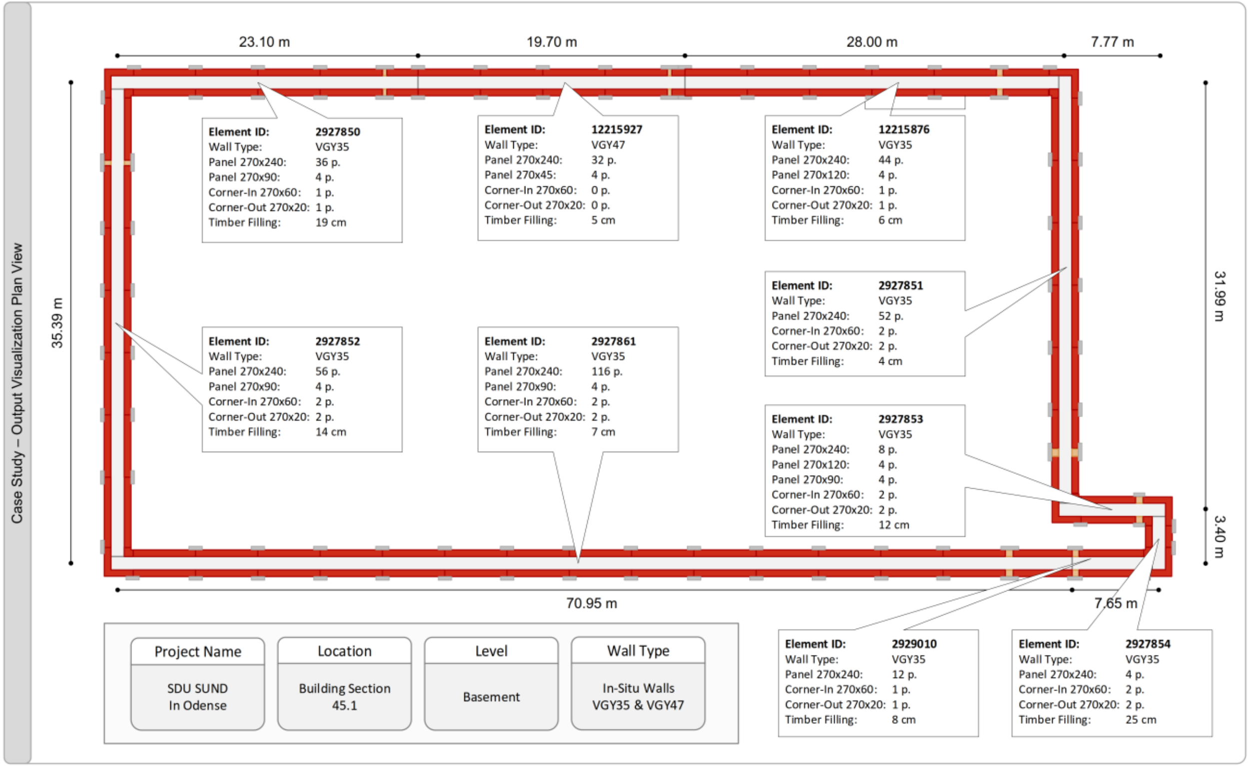


VICO 3D View



exigo

Case Study – Results

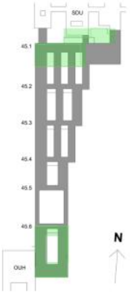


Case Study – Results

Power BI Dashboard Visualization – Page 0: Project Overview

Project Information

Project Name:	Nyt SDU SUND
Location:	Odense
Project Type:	Public, New Construction, Rural
Building Type:	Healthcare Science Faculty
Building Size:	50.740 m² brutto
Levels:	N-1, N00, N01, N02, N03
Building Sections:	45.1, 45.2, 45.3, 45.4, 45.5, 45.6

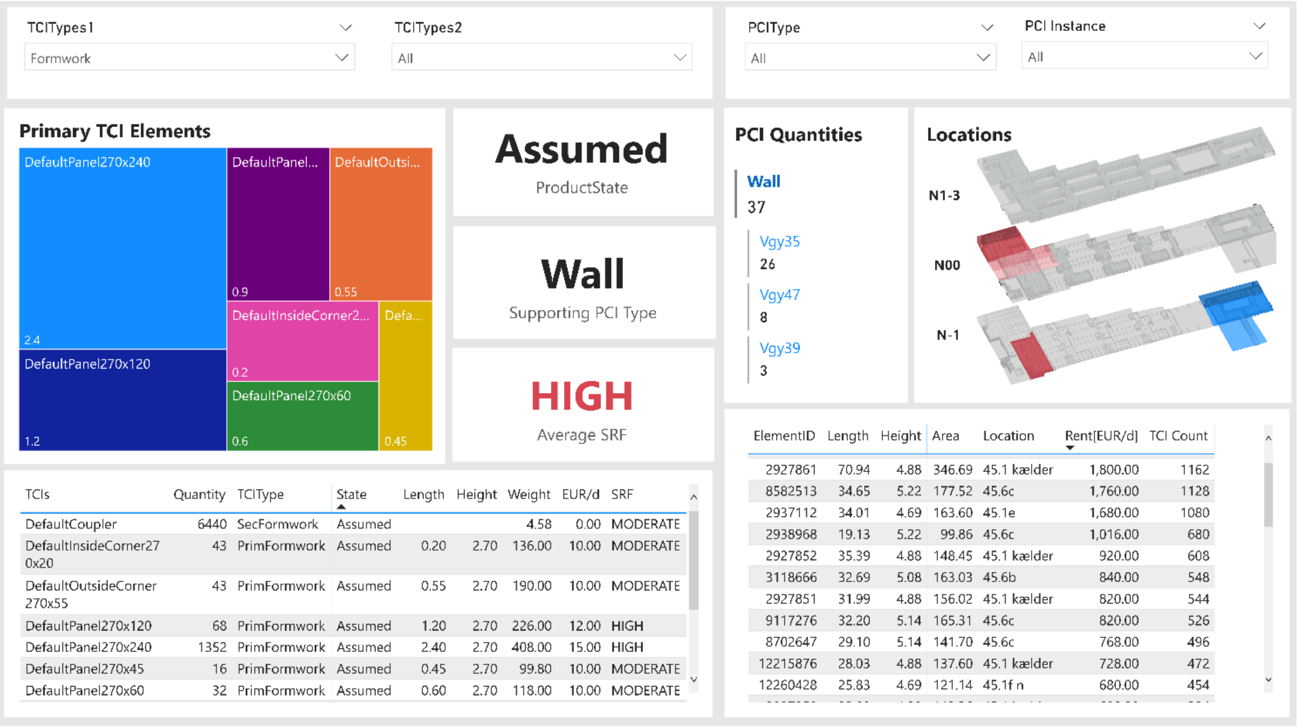


Content of the Dashboard

TCIs/PCIs	TCI Information with specifications and quantitites PCI information with specifications and quantitites Location Slicer for PCIs
TCI Utilization	TCI allocation over time Daily TCI quantities Daily TCI utilization compared to stock Comparison between static stock (current practice) and dynamic stock Cost information
TCI Tasks	Gantt diagram, showing all tasks which involve TCIs TCI utilization time and timber filling per task TCI quantities per task and safety-risk-factor

Case Study – Results

Power BI Dashboard Visualization – Page 1: TCI/PCI Information

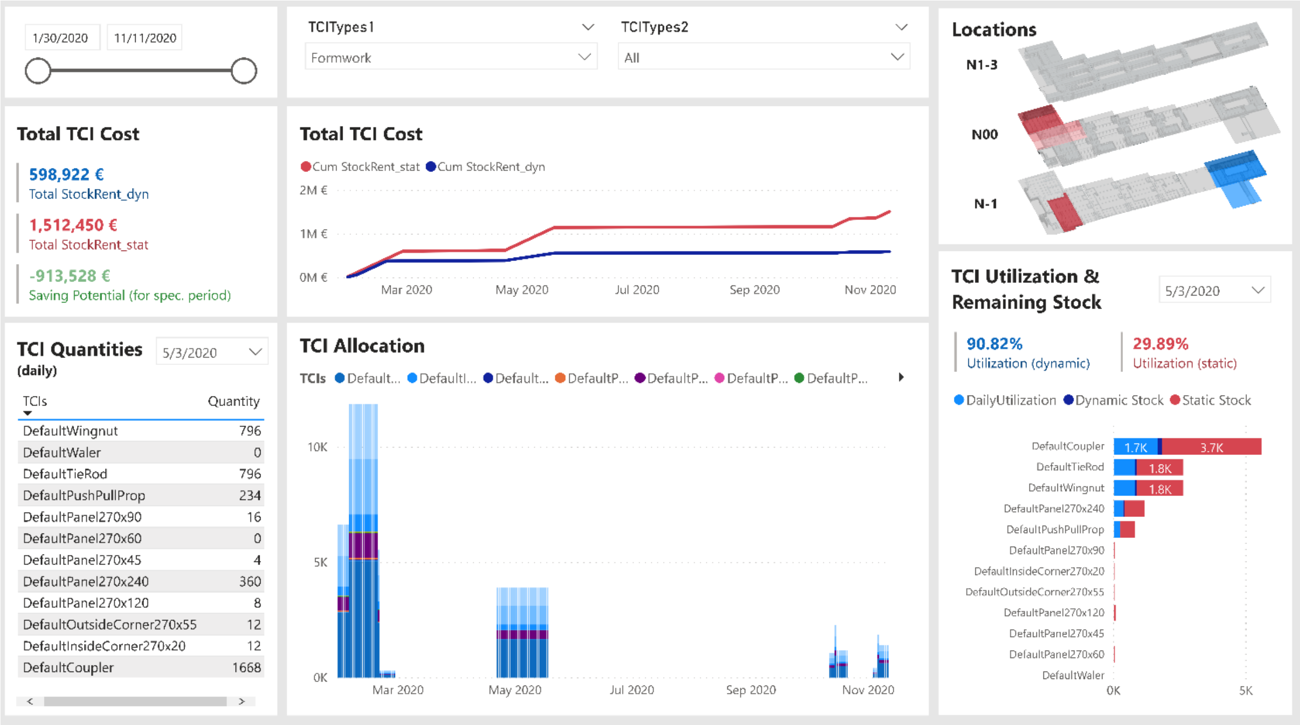


TCIs	Quantity	TCIType	State	Length	Height	Weight	EUR/d	SRF
DefaultCoupler	6440	SecFormwork	Assumed			4.58	0.00	MODERATE
DefaultInsideCorner270x20	43	PrimFormwork	Assumed	0.20	2.70	136.00	10.00	MODERATE
DefaultOutsideCorner270x55	43	PrimFormwork	Assumed	0.55	2.70	190.00	10.00	MODERATE
DefaultPanel270x120	68	PrimFormwork	Assumed	1.20	2.70	226.00	12.00	HIGH
DefaultPanel270x240	1352	PrimFormwork	Assumed	2.40	2.70	408.00	15.00	HIGH
DefaultPanel270x45	16	PrimFormwork	Assumed	0.45	2.70	99.80	10.00	MODERATE
DefaultPanel270x60	32	PrimFormwork	Assumed	0.60	2.70	118.00	10.00	MODERATE

ElementID	Length	Height	Area	Location	Rent[EUR/d]	TCI Count
2927861	70.94	4.88	346.69	45.1 kælder	1,800.00	1162
8582513	34.65	5.22	177.52	45.6c	1,760.00	1128
2937112	34.01	4.69	163.60	45.1e	1,680.00	1080
2938968	19.13	5.22	99.86	45.6c	1,016.00	680
2927852	35.39	4.88	148.45	45.1 kælder	920.00	608
3118666	32.69	5.08	163.03	45.6b	840.00	548
2927851	31.99	4.88	156.02	45.1 kælder	820.00	544
9117276	32.20	5.14	165.31	45.6c	820.00	526
8702647	29.10	5.14	141.70	45.6c	768.00	496
12215876	28.03	4.88	137.60	45.1 kælder	728.00	472
12260428	25.83	4.69	121.14	45.1f n	680.00	454

Case Study – Results

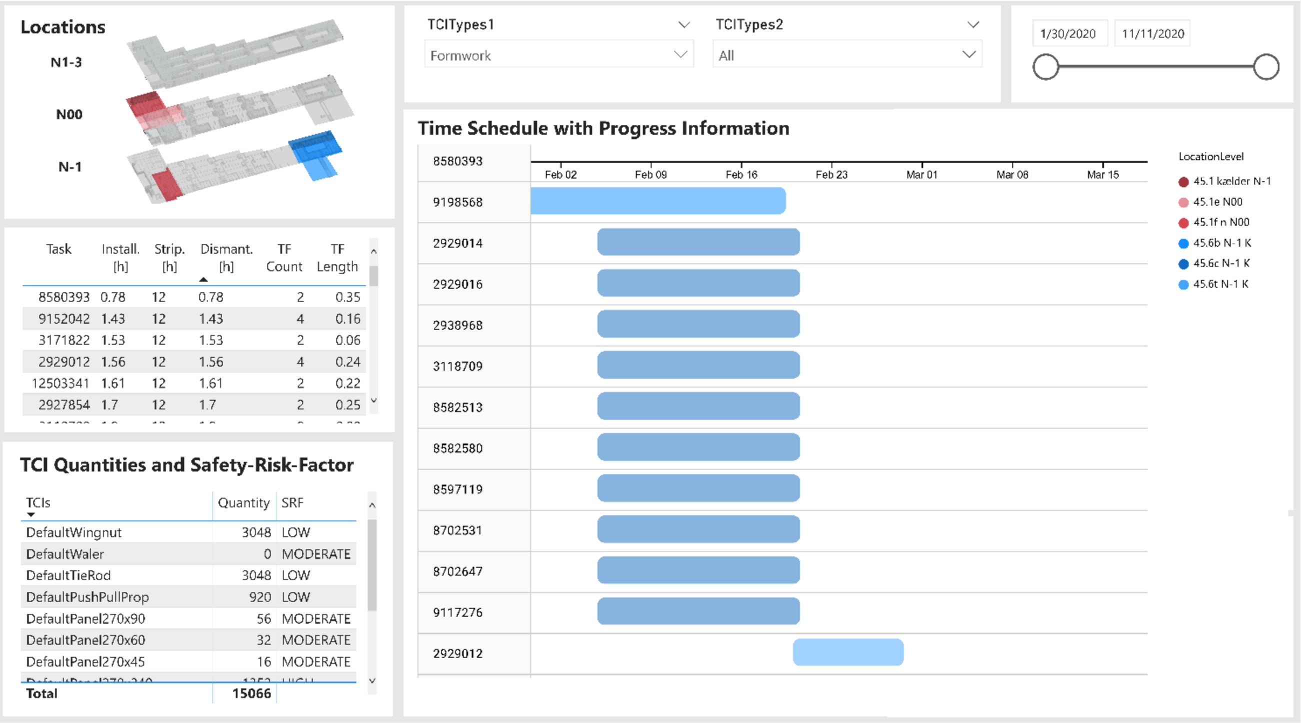
Power BI Dashboard Visualization – Page 2: TCI Utilization



exigo

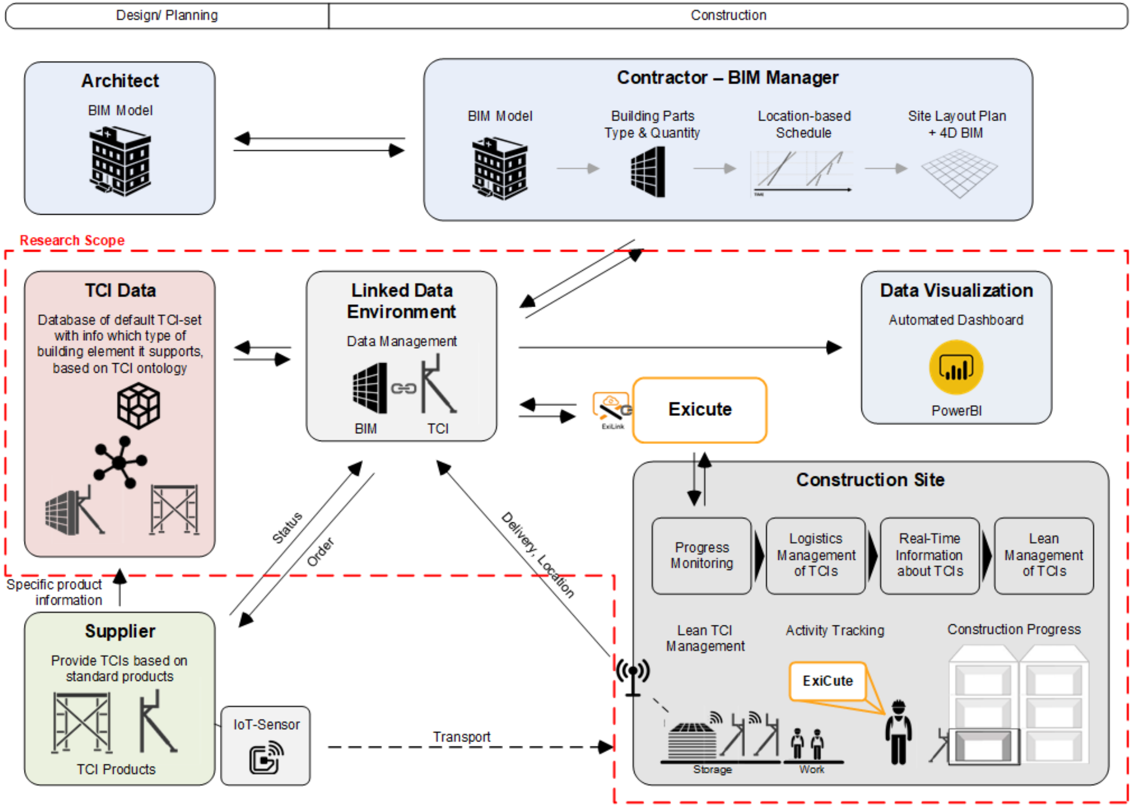
Case Study – Results

Power BI Dashboard Visualization – Page 3: TCI Task Information



VI. Ideal Future Scenario

Ideal Future Scenario



Ideal Future Scenario

1. AEC stakeholder publish their work via Linked Data in a secure project environment
2. Building code requirements, client and other regulations are available through Linked Open Data
3. Supplier publish their product catalogues via Linked Data to take part in the project tender

Automatic creation of location-based TCI-utilization plan with passive resource monitoring, based on existing BIM-data

Real-time tracking of construction resources via IoT-data integration

Lean and integrated management of TCIs leading to improved productivity and safety on site

Questions/

Feedback?

Appendix 6.1

Answers of Interviews for State-of-Art Report

Findings from the Expert Interviews (Chapter 2)

No.	Question	Assumption/ Initial Comment	Interviewee
1	**Problem Space**		
1	Do you agree on this and where (regarding site and logistics management) do you see the most potential to overcome these challenges?	In literature, poor productivity and safety issues are identified as common problems on construction sites, caused by elemental constraints and shortcomings in the industry (referring to the chart below).	
	- Very conservative industry and lack of innovation as main drivers - Primary drivers for not getting the full potential our of site and logistics management. Reason is the lack of innovation as well as the conservative industry. Also education as workers don't have the skills to use technology. - Mentality of CM is to daily face the challenges of site logistics, moving material around without a long-term master plan - Designer are estimating site layout in big projects although they never worked as a site manager. A lot of theory. Lack of practical experience - And "I experienced that often that when it gets into a hand of a site manager. He can spot the first 20 mistakes immediately." - On the other side, you have the site manager who cannot use Revit or another modelling software. His knowledge stays in his head and he manages the site from day to day because he knows how it should be done. Dare him to be sick. **Potential** Mostly concerning productivity but safety is always an issue as well. Lack of site planning in general. --> Contractor integration into scheduling.		**Consultant 1**
	- Generally agrees on the assumption and classifies productivity and safety issues more into internal challenges - When planning a construction project, it is important to prioritize the planning of what's happening on site --> underprioritizing construction site plan, e.g. procurement schedule - Current practice is characterized by poor planning which leads to a non-consideration of constraints on site and a poor overview of procurement, usage and rental processes - Most potential in the **planning phase** and related to that in the **monitoring phase** --> enable a bilateral information flow between planning and construction for adjusting what is planned - Logistics problems are mainly related to the work of subcontractors and thus, planning should also be considered from the detailed perspective of subcontractors - However, subcontractors cannot cope with this responsibility as their approach is more based on a day-to-day problem solving mentality --> "subcontractors are not looking as far enough ahead to have that degree of planning that we need" - Information technology can help to manage this, especially the more detailed and complex it gets		**Consultant 2**
2	How can technology improve site logistics management and why is updated data from the construction site important?	Missing integration of BIM and IT at the construction site is a big shortcoming of the industry, resulting in weak site monitoring and project management because of one-way information flow and lack of structured data?	
	- WHY: There is no incentive to use BIM on site because the construction workers want to focus on their main activities and don't want to give feedback to the model, which requires a lot of work. However, an updated model is super useful as it holds updated data and site or logistics managers could get information about construction progress automatically and don't have to use their time to get the information. - "That gives the construction management a great overview of where things are happening, what activities are being made where" - Not much consideration for TCIs, but it would be beneficial! But also needs to get updated feedback of these items to manage the construction site properly. - Updated data about progress of the activities is most important, because that's where the logistics, the needed TCIs and materials is linked to (Information about type, quantity, location, use) - In Morten's opinion Exigo is the first company trying to fully integrate in in an effective way to report progress in still on a detailed level (Exicute)		**Consultant 1**
	- Logistics in general is a big problem in construction as there is little space and things need to be moved around constantly (Equipment is blocking the site causing waste in construction activities) **-->** This requires a dynamic planning of the complex construction processes - CiFe-Study: How many alternatives do you look in to before making a decision? --> 2.5 alternatives per decision general in construction and on site this number is even less - Due to construction complexity decisions in construction are made on very little alternatives and a simple analyze of these alternatives "So if you if you want to buy a car, you look at four or five cars and when I wanted to buy a house I looked at 20 houses, but in construction, we often make decisions on very few alternatives." **-->** Automatically generate alternatives and evaluate it on the design outcome (based on different indicators as costs, time, sustainability or resources) **-->** Sometimes it is better to trust technology (machine learning and AI) over human knowledge --> Rules for algorithms can be derived from best practices or professionals and the solutions can be derived automatically from technology BUT sometimes only the precise and required outcome is defined and AI is iterating the best path for getting the output - Another big issue in construction is that nobody wants to write something down, track and monitor processes and progress --> IT can help to receive this data automatically		**Consultant 2**
3	From your experience, how are temporary construction items managed and what would be the benefit of more and updated data about these items?	There is a lack of attention and information regarding temporary construction items. Temporary works is only included as an estimate or percentage of the total cost but is often not planned and monitored properly.	
	Deployment: - "Either tenderlist where the designer lists up a lot of different potential things he thinks that the site might need for temporary works. Or it is just a percentage of the total cost and the designers will never be wiser because the information flow never gets back." - TCIs are just ordered on an assumption and deposited until needed. sometimes it is not needed, or sometimes the site is running out and has to reorder TCIs. I--> **iterative management approach from day to day.** - Would be much easier if this information is linked to the model and a 3D-site model would be created - Site manager is the only guy who can manage the site. If he is sick, everything falls apart. "I'm scared of, if a guy like that leaves or gets sick for a week..." --> The site plan is solely in his head --> Blocking information flow as it is not documented and planned. That's the problem! **Operation**: - No information about equipment and TCIs when to use them. Will be looked for and found immediately before or during the activity has already started. Look-ahead plan and lean management isn't working. - No information means a big stock of TCIs on site to prevent shortcomings, resulting in a lot of inefficiently used space on a construction site. **Benefit**: - Planning ahead what TCIs are needed for the specific building parts already in design phase. With contractor integration in the design phase, this knowledge can be achieves and established early (IPD) - If the linked data is there, the contractor would know exactly the amount if TCIs he needs to order and when and for which location. --> Based on progress monitoring, you can then just adjust the site management and logistics planning as well.		**Consultant 1**
	- **Example**: In a previous job, a situation was experienced where an intern was supposed to find a movable scaffolding platform on site but nobody knew where it was and they paid the renting bill for two years --> In the end the construction manager paid much more in rental fees than the material would have cost because nobody knew where it is - Assumption is correct --> TCIs are not really planned only a percentage of the total costs and it is not sure what is there on site, who is using it (booking of tools, machinery), and sometimes they just disappear because they are neither planned nor tracked --> Have some positive impact in costs but a lot in **time saving**! - HILTI has a system with RFID and GPS sensors ⍰ People are more and more aware of it		**Consultant 2**

Findings from the Expert Interviews (Chapter 2)

No.	Question	Assumption/ Initial Comment	Interviewee
2	**Solution Space**		
4	What data would be beneficial to track? What type of temporary construction items (e.g. formwork, supporting struts and safety barriers)?	Real-time tracking of temporary construction items has potential to reduce waste, costs and safety hazards.	
	- Data to track: Picture of element, weight, size, count of different types, function, location, safety risk factor (1-10) --> Extra attention on specific type of tasks when installing TCIs - Real-time information about formworks and scaffolding and supporting structures. That's something that would be nice to know where it is at all times, as these items are constantly on site, moved around and reused frequently. For big machinery, more advanced IoT could be used to measure their operation.		**Consultant 1**
	- How to plan TCIs depends a lot on the type of TCI: 1. Bigger items as mobile platforms, bigger scaffolding, site trailers, fences, bigger machinery, which all does not float around frequently in a construction site can be modelled as a site model --> Would be great to automatically integrate this in BIM 2. Items that are moved around and used frequently should be estimated and planned but doesn't have to be visualized in a 3D-model --> Equipment company rentals might already offer the service of planning formwork based on a 3D model - Formwork as a TCI example makes sense because it is important that it is planned --> Needs to be planned by the subcontractor (e.g. supplier) as it needs to fit their work processes --> Therefore, data from BIM and schedules need to be linked to TCI data from subcontractors, in order to plan (not a project based and closed application) --> Linked data can be interesting to use in this case - **Example**: iTWO software is using rule based planning for its estimation system by applying quantity queries on properties from BIM objects in a model --> iTWO can code through the given BIM model to extract quantities of things that are based on rules and geometry (e.g. meters of safety barriers around holes in slabs)		**Consultant 2**
5	Where do you see the most potential as a focusing area of the research? What should be the primary research objective?	Five recommendations for developing a solution are derived from the state of art review.	
	- 4D-BIM is already existing, just not frequently implemented - In order to realize step 2-5, step one needs to be established first --> Therefore the focus should lie on the development of a simple way to plan TCIs and then use this information to improve logistics and site management		**Consultant 1**
	- First: Make better planning to integrate TCIs but in a simple way --> no geometry needed - Then: "If you fix the planning, the next step that makes your planning better is to have better and faster data flow on how your site actually looks at what is going on site." --> **Tracking** - Geometry of TCIs is not needed in a model and therefore a rulebased interpretation and quantity take-off of these items with information about location is sufficient --> focus on quantities, when (time) and what (type of TCI) and where (location) - With IoT, the location information can then be tracked and verified in comparison to the schedule - TCIs can then be visualized on a location level with the schedule to review what type and how many TCIs are needed where and when on site rather than on a detailed model level. --> That's all what matters - Interesting is also the feedback loop for design consultants as an automatic and rule-based planning might has an impact on the design --> If the rule tries to use as much standardized formwork as possible to increase productivity, the design should be adjusted according to this --> Answering the question, to what degree can standard formwork being used for a specific design, might define a new criteria for evaluating a design alternative		**Consultant 2**
6	How can temporary construction items be tracked? How should the tracked data be received, processed and then used to add value to the project?	An IoT- and cloud-based platform for data processing and exchange will enable a real-time tracking system.	
	- The reason why RFID tagging hasn't been fully integrated into the construction industry is because there is a of resistance from the workers to manually scan the tags as their sensor range is pretty small. If somebody forgets to scan an item, the whole dataset is wrong and will confuse the schedule. - Sensor needed that automatically sends data to receiver --> **5G technology** for automatic tracking on a precise level, cheap and no need for a local transmitter. Only a small antenna needed communicating with the cellular connection (mast at site if no connection) - Sensor would need GPS for the exact location, gyroscope for movements and storage space for holding information about the task and item. - **Requirement:** Technology which doesn't affect workers job. Construction workers don't need to do anything about it because they have their jobs because they want to build not because they want to be logistic managers and that would be necessary - Cheap (50-100 crowns) and easy to implement in order to make business case out of it		**Consultant 1**
	- IoT technology is already used intensively in other industries and can be copied in a mature level to construction industry --> Parameter for implementing IoT-tracking to improve the process is costs (if it is economically beneficial) --> HILTI on Track: GPS Chip which has a data net (5G) to send small amount of data about location of HILTI tools --> IoT-sensors must be provided by the supplier --> Also benefit from them where their products are --> intrinsic motivation of the supplier to use IoT, but the technology can then also be offered as a service to construction sites to track these items on site. - Future Scenario: Boston Dynamics SPOT-dog with RFID scanner can make a tour on site at night and register every time he comes close to a RFID tags and by that track items on site and see where items are located --> Then based on these findings, a location model can be made out of it		**Consultant 2**
7	Is it possible to extend the application Exicute and use it in this thesis?	Recommendation 2 and 3 can be integrated into Exicute, providing an existing platform to test the system.	
	Yes, for progress monitoring and also the link to visualize data		**Consultant 1**
	Question not asked to the Interviewee		**Consultant 2**

No.	Question	Assumption/ Initial Comment	Interviewee
Findings from the Expert Interviews (Chapter 2)			
3	**Other comments**		
	Activity Tracking --> Iteratively developed the idea by reasoning and looking at it, from a business case perspective - Link building parts of the model to TCI-requirements in a database and get updated information with progress monitoring of activities --> a resource graph of the used items, using progress monitoring of related tasks to present passive real-time information about TCIs - The easy way: When planning, create a small scale database with information and data about TCIs (formwork, etc.) connected to different location based activities --> track the number of construction items, but the task which was related to the construction items "you have planned it, because you know the size of it. And you have planned that they need this much formwork to do this activity in that location" --> make a small ecosystem where it is all integrated **Benefit**: - Benefit from having it in your plan, because then it's set up, so you can easily track it when you are operating the site. - Benefit from tracking the quantities of it of each type you need and when you need it - Only ONE INPUT is needed --> progress monitoring will result in information about (the cost of, the time, the schedule, the logistics, the site operation) --> Raise productivity, less waste on construction site, as Site Manager or Safety Manager can focus on their real job **Task-Flow:** - a demo of having a small data warehouse which has the items and you can link it to activities and stuff		**Consultant 1**
	Proof of concept: - Difference in activities between building a nuclear power plant and a kindergarten --> 80% of the activities was were the same, you're just in a different scale, but you still need to do the same steps. So you I think you could definitely rather quickly build up a database where you have these, you know, more and less generic tasks with the generic equipment that you need. And machinery and temporary constructions.		**Consultant 1**
	And if you've assembled at your peak time, if you need 50 forms to do your formwork. But you only at that peak time, you have a whole year where you only need 20 pieces beforehand. Then it will be nice that you could automatically just say to the logistics centre at your contractor headquarters something that okay, send out 20 pieces, so it arrives at this date. And then when you are reaching, you know, the next step of the piece you said 30 more stuff like that could be a nice thing to like make a small ecosystem where it is all integrated		**Consultant 1**
	Meeting with Ole - Use of reusable formworks in Denmark, which are that cheap - Ask Ole if they rent TCIs or have it in a warehouse **Project:** Use of plans and construction site of SDU in Odense (talk again to Morten) Case: an example of that and then check with the contractor how the system is simulated, then we can ask them is that the amount of forms you actually have on site? You know, yeah, it could be an interesting to check with a reality to have something.		**Consultant 1**

Appendix 6.2
Answers of Interviews for Concept Development

Findings from Expert Interviews (Chapter 5)			
No.	**Question**	**Assumption/ Initial Comment**	**Interviewee**
	Key Question		
0	How can productivity and safety issues in construction be resolved by integrating temporary construction items (TCIs) in the logistics and site management process?		
	Not relevant		**TCI Provider 1**
	Not relevant		**TCI Provider 2**
	Productivity and safety goes hand in hand, and either cannot be lacked because if safety is left out the workers on construction site cannot do their job efficiently when they feel unsafe and must tread carefully and thus a decrease in productivity. Here in the SDU SUND construction site we use temporary construction items such as barriers which are placed around excavation pits to ensure the safety of the workers. As well as the crane tower to lift all the heavy materials down to the pit for the workers.		**Client 1**
1	**Problem Space**		
1	What products do you provide for construction sites? How's the future demand regarding these products expected?		
	- Storage yards/ material stocking locations, Construction site fences, Setting up of access scaffolds, stairs, stair towers and ramps, temporary facades, cranes - Setting up of water and power supply on site		**TCI Provider 1**
	- Formwork and Scaffolding - PERI standard forms make approximately 95% of all used forms at PERI - PERI is trying to get more actively involved in the beginning of a construction project to already place their expertise --> Formwork decision already have a impact in the design phase but most focus is on construction phase - Future demand is expected to stay high as concrete is still the most frequently used construction material and prefabricated elements are mainly used in buildings as stadiums, carparks etc. - PERI also holds some shares at startups that try to disrupt the building industry with their solutions (e.g. 3D-House Printing from COBOD)		**TCI Provider 2**
	Not relevant		**Client 1**
2	How do you supply construction sites with your product and what services do you provide with your products? Do you use any technology to facilitate this process?		
	- Ajos takes responsibility for the establishment and operation of construction sites as a construction site contractor. This includes the heavy tasks such as the setting up and operation of machines and equipment, monitoring, logistics and the dialogue with the authorities as well as the co-ordination with the other parties at the site and service tasks such as cleaning, canteen operation, janitorial functions and security guard services, etc. --> If you ensure cranes, hoists, site huts and modules, or other equipment, at your construction site, then your subcontractors can do those tasks they have been hired for. **Services**: - Logistics management, Subcontractor co-ordination, Waste management and sorting, Setting up of gates, booms and central islands, Establishment and management of storage yards/ material stocking locations, Construction site fences, Setting up of access scaffolds, Setting up of stairs, stair towers and ramps, Setting up of temporary facades - smartBYG - the Ajos Web-based logistics program - makes it easy to manage the logistics at your construction site, so you avoid traffic bottleneck - For larger and more complicated construction sites, Ajos offers digital simulations of the construction site arrangements using Virtual Design and Construction (VDC) technology, which we have access to via MT Højgaard. Tell us all about your plans - and receive a detailed picture of what your optimum construction site could look like. By using VDC, we can optimise the logistics, placement of equipment, site hut clusters, access routes and the like. The simulation ensures that your construction site is established as efficiently as possible - and that you avoid expensive errors, BEFORE you start the construction work. When construction starts, drones can assist in creating overview pictures and performing digital progress reporting.		**TCI Provider 1**
	Services: **- Buy or Rent products from PERI, Logistics planning, Engineering, Maintenance and digital services with BIM Competence centre** **- Buy: If contractors buy the formwork and scaffolding elements from PERI, it is their responsibility to plan and managed their use for the construction industry** **- Rent: PERI is taking an active part in the construction process and digitally plans quantities, task sequence, logistics etc. of their products based on the given project information (e.g. from a 2D/3D model)** **Digital Services:** **- Laser & Drone scanning of existing buildings for generating models based on photos and point-clouds** **- Data processing with different software applications and formats (IFC, rvt, etc.)** **- PERI CAD --> 3D modelling of formwork, scaffolding solutions based on building model** **--> Automatic generation of material quantity lists** **- Product Libraries of PERI standard solutions as plugin in modelling software** **- Visualization and simulations (How-to-Animations --> Easy access to product-specific animations supports safe and efficient execution)** **- Integrated and lean workflows --> Linking of designs and animations directly in PERI CAD** **- Cloud-based Design coordination & collision checking between PERI model and building models** **- Linking important documents at specific building parts** **- Checklists for safety and maintenance work (Minimized risk of accidents, Guarantee of planned quality, Sustainable documentation of responsibilities)** **- Issue/ Defect Management** **- QR and RFID codes for the exact identification of different elements with link to the use plan of the elements based on the 3D-model and schedule information** **--> Optimized construction site employment and management of TCIs** **- Augmented and Mixed Reality**	- General Workflow: 1. Receiving Project Data 2. Transforming Data into usable 3D-Model (IFC, DWG, NWG) 3. PERI CAD planning of formwork and scaffolding solutions based on 3D-model 4. Model processing 5. BIM 360 management process	**TCI Provider 2**
	Not relevant		**Client 1**

Findings from Expert Interviews (Chapter 5)			
No.	**Question**	**Assumption/ Initial Comment**	**Interviewee**
3	How are temporary construction items considered in a construction site regarding budgeting, management and monitoring?		
	The assignment can be described in the BSB Construction Case description and job description that is on any project. It leans up to contract schedule that you build on. In relation to safety, work must be planned so that it complies with applicable rules and legislation.		**TCI Provider 1**
	1. Budgeting/ Planning: If supplier is not integrated into site planning & logistics, contractor used a Lump-sum value in % estimated based on gross value of the building to generate an approximate amount of TCIs --> If supplier is integrated, all digital solutions can be applied to support the construction process 2. Management: TCIs are ordered to serve the entire project. This surplus on elements causes storage & logistics issues and results in high costs for the use of TCIs as their usage is not optimized 3. Monitoring: Not yet done from contractors, but supplier could enable QR or RFID codes to monitor the use of their products		**TCI Provider 2**
	TCIs on site: Formwork and its components, supporting props, electric cables, lighting, water supply and drainage, site facilities, cranes, driving/walking path fences and signage, orange posts around excavation, steel plates, lifting platforms, concrete barriers **Planning**: First planned as a percentage of the total costs in the official offer, developed from the owner and accepted by the contractor --> Based on design, the total amount is estimated for the whole construction site --> Contractor is then ordering on a "just-in-time" approach the TCIs which are needed for the upcoming tasks on site (Already a quite lean approach, but still only based on a rough estimation and the experience of the contractor) --> Is not scheduled in detail. Only estimation for whole project but no information is there how much (quantities) is needed for each phase or even construction activity **Budgeting**: Initial from owner in the official offer but during construction, invoices are sent from the contractor based on the progress --> Costs are estimated and then invoiced by the contractor. Little transparency, which was also leading to missing fences for the construction roads in the site budget (Walking roads have not been planned properly and now much more fences are needed) --> If TCIs can be quantified in a simple way for each construction activity, a better estimation can be done for TCIs --> Rough planning will lead to changes that lead to cost overruns Budgets of construction items are organized monthly for the whole length of project and is managed when entrepreneur asks for invoices by requiring for documentations about items and quantities if suspicion arises. **Monitoring**: The construction activities/ items are monitoring by conducting inspections on the construction site. **Use of Formwork**: For supporting Elements in the lower levels as Foundation, Basement Walls Information is planned when it will start and end (Not detailed how long to it will take to install, poo concrete and dismantle it) --> But not specific on TCIs (ask Morten again if it is included as part of the schedule activity) --> Can be used though to passively plan them!		**Client 1**
4	How is the construction site layout and logistic planned and managed? What information/data is considered in this process?		
	Not relevant		**TCI Provider 1**
	Not relevant		**TCI Provider 2**
	The site layout and logistic is planned in accordance to the process schedule. It is planned in such a way that it is most convenience to execute tasks regarding the safety of the workers on construction site. The entrepreneur’s suggestions on how he would execute the tasks are also taken into considerations. As for the management, it is done by inspections at construction site as well.		**Client 1**
5	What items create the most difficulties regarding site & logistics management on site? Where is the most potential to make improvements?	Items, such as formwork and supporting structures are used repeatedly during construction. These items produce waste and block construction progress because they are not properly considered in construction management.	
	- Interim installations such as electricity, light, water, heat, closing the facades for weathering, ramps and level jumps in floors, cranes and construction site lifts. Logistics management of materials in relation to how many contractors are set to work on the individual floors according to schedule. If there are several subcontractors gathered in the same room, it is to be regarded as common areas with the requirements to these places		**TCI Provider 1**
	- Specialized formwork - Formwork in general has a great improvement potential as it is often moved around and reused on site - To much material on site which is not used		**TCI Provider 2**
	There has been some difficulties regarding excessive amount of water from groundwater as well as bad weather. High voltage power lines which have also been causing some troubles because it has been taken into considerations at a timely manner. Also, the uploaded information/drawings how to implement the tasks on site is very crucial as well. Obtaining information on existing cables/wires on early stage so it can be integrated into schedule. --> Because TCIs are not planned in detail, there is no transparency and real information about when and where which types of TCIs are needed on site. Having the updated information based on the construction progress, the would 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.		**Client 1**

Findings from Expert Interviews (Chapter 5)			
No.	**Question**	**Assumption/ Initial Comment**	**Interviewee**
2	**Solution Space**		
6	What data or information would be needed to improve the management of these items? How can this information be obtained? (e.g. BIM, sensors, supplier information, site progress etc.)	--> Formwork as a service	
	- If TCIs were already embedded in the tendering process, planning interim installations and their location over time could be optimized. - One can simulate the construction site and logistics via BIM		**TCI Provider 1**
	- Specific info about products (number, weight, area, dimensions, static capabilities, supporting elements, How-to-Animations etc.) - Info about 4D/ 5D planning to link to TCIs - **Status management:** (Ordered, delivered, stored, in use (erected, ready for concreting, Dismantling), storing, ready for pick up --> Planning and then sensors to monitor --> Goal is to obtain information as easy and quick as possible		**TCI Provider 2**
	Updated information about TCIs and take them into account in order to be able to determine whether they are a hindrance to the tasks that need to be executed on the construction field. If they directly support a task, they the information should enable a lean management, so the items are stored where they are used later on. The planned amount will also give the management a reference to check the actual installations. --> Information about TCIs would benefit both the contractor and owner representative for CM by increasing transparency, but it directly affects the contractors work. The information can either be distributed with the Exicute application, collectively with the current construction activities		**Client 1**
7	Is it possible to automatically generate the number of standard formwork based on geometry of building parts? Does your company have such a solution?	By linking the TCIs to their related construction activity, it must be possible to derive amount and type of TCIs.	
	not answered		**TCI Provider 1**
	- Normally Engineers are planning the formwork and scaffolding design for every construction project using PERI CAD - PERI Quicksolve is a simple application that generates formwork solutions by using a quick sketch and some parameters of wall elements - PERI automatic planning is based on rulesets and assembly and use manuals of their standard products --> Rules: How much formwork top-up, Push/Pull props, connecting elements --> Visual scripting was used in PERI for defining the rule-based algorithm to automatically generate formwork solutions for given geometries --> C++ file was generated which could be imported into CAD system to include TCI information - Supporting elements can be defined via average values (Panels, connections, anchor, Push/Pull props, concreting platform **--> Define ruleset based on assembly and use manual of a standard product at PERI (Mostly used is Maximo formwork)**		**TCI Provider 2**
	Could be possible with a algorithm that takes in information from the building model and the available forms		**Client 1**
8	In your opinion, how will the proposed setup improve productivity and safety on site? How would you as a supplier/ construction management benefit from it?	The proposed process improvement of site & logistics management regarding TCIs is proposed. The main idea is to link quantities of temporary construction items to the building activities of a BIM plan and with that receive updated information about when and where specific TCIs are used in the construction process.	
	not answered		**TCI Provider 1**
	- Productivity and Safety are also aspects that are most important for PERI - In general, having a plan and real-time information about the utilization of TCIs always improves productivity and safety on site - Solution data graph can also be equipped with ISO standards and safety regulations - Extension to use IoT-Sensors and supplier information is very useful to complement the proposed solution, but works also without		**TCI Provider 2**
	- The proposed setup might have a positive impact on the productivity and safety because the entrepreneur can always see when he/she needs to have the TCIs ready for the upcoming tasks. It might also save both entrepreneur and construction site management team time as it is already planned for them. One would always now what types and quantities are right now on site and will be needed later - An automatic and updated utilization plan lessens a lot of burdens from both parties --> You know how much the quantities are and it is transparent to the parties --> Safe time for estimation and have a better estimation. - In Safety meetings it is discussed what needs to be done . If the utilization plan of TCIs will notify the construction professionals about the safety risk factor of each construction activity, based on the TCIs, activities which need special attention due to higher risk factor can be addressed in the safety meeting and its weekly look-ahead plan and or the daily meeting of the contractor. --> Notification for construction workers if a TCI need special attention due to a higher risk factor --> Manual or simulation with proper installation of the item - Safe space and costs when you don't need TCIs because now you would still pay the monthly rent --> **Rent out and Re-Rent** --> Removed two containers because they didn't need it anymore --> Fences e.g. is paid by meters per month, so there would be a high incentive to rent it out again if it is not needed - Depends on the cost-benefit if to rent it out and re-rent it or to just keep it!		**Client 1**
9	Who would benefit from the proposed solution?		
	not answered		**TCI Provider 1**
	not answered		**TCI Provider 2**
	Would help both parties (construction manager from owner and contractor) as updated information about how much of each item is used when and how long (to help contractor with their planning but also to check the budget if all budgeted items are used (Now everything is planned manually) - **Owner**: Costs (checking), Costs (renting costs), and more - **Contractor**: Reliability of planning, make money, Efficiency of construction process if improved --> Delay is mitigated (no fines) - **Supplier**: Supplier can have a more dynamic rent system where TCIs can be moved around different construction sites more dynamically as updated and transparent information about the utilization of TCIs is available for all relevant stakeholder		**Client 1**
3	**Other comments**		
	It was actually never the case before to plan in this detail on each activity --> It is more an estimation of the whole project It would also take the task easier for **the construction manager** from the client side if he know what type of material/ items are need in a specific month and the quantity --> Knows how much money to pay for the contractor		**Client 1**

Appendix 6.3

Answers of Evaluation Interviews

No.	Question	Interviewee
	Findings from Evaluation Interviews (Chapter 6) *red = comment	
0	**TCI management (for Contractor only)**	
0	From your experience, how are temporary construction items e.g. formwork elements planned and managed for construction projects?	
	- Maybe it's obvious but the main the main business model in Denmark here is renting a formwork not buying	**TCI Provider 1**
	- Different on every project --> On small project, just an estimation. On some project where a site model and 4D plan is created, TCIs are considered more in detail - However, TCIs are very important to consider as they affect time, cost and quality of a project --> better planning = reduce waste, have transparency - Many construction manager/ foremen order a lot of formwork elements, to be sure that is will be enough for the project! --> **Security** --> with a more transparent management of these items, insecurities can reduced and thus, the amount of elements on site are reduced to the minimum	**Contractor 1**
	- Over the las 10 years, TCIs have been considered along the BIM-based project delivery to optimize the production and the planning as well as economy regarding the number of items to rent/buy and use on the site. - Example project: Nordea project --> Twice a week a meeting with the construction crews regarding how they should handle the TCIs (material, machines, etc.) on site in a very efficient way so all the crews knew what was available when and where --> Weekly meeting for discussion and update based on dashboard! --> Internal planning system called to combine location based planning from VICO and BIM on the construction site for the planning and management of TCIs	**Contractor 2**
	- In my company, we already plan our projects from the building model, and afterwards we plan the project on site, and then we compare those two elements and make it work together. - Own specialists calculate the TCI requirements for the site model --> What is missing is the process in between from the planning to the site and there the solution presents a good way to bring the required data to the site, enabling a just-in-time delivery and takes into account the progress delays or changes	**Contractor 3**
	- Temporary construction items are only included as an estimate or percentage of the total cost but is often not planned and monitored properly. It is not sure what is there on site, who is using it (booking of tools, machinery), and sometimes they just disappear because they are neither planned nor tracked.	**Consultant 2**
	- Planning of TCIs is still done in a very primitive and manual approach based on Excel data which is extracted form the building volume - Based on this rough estimation, TCIs are ordered from supplier - On site, formwork is getting lost and stolen because of there is no transparency about what items are needed when and where --> As no transparency of what items are needed where, order enough items --> Overstock or Understock on site	**Consultant 3**
	- Current practice: In worst case scenario you just order what you think is needed on site - Sometimes, you considered TCIs in your site management, but most processes still wouldn't give you a precise number and therefore, the stock can be too much or too low, depending on your estimation - During the project, equipment is ordered on short notice as the construction manager further develops the construction plan - Nowadays nobody counts things on site --> If returned to supplier, there must be a standard percentage of maybe 5% which covers the waste (losing or damaging items) --> As PERI said with linking this information to the delivery and stock numbers of the supplier!	**Consultant 4**
	- TCIs are mainly considered in site planning as an estimation, based on the existing building data --> No precise numbers are used and the main driving force of the TCI quantification is to ensure that the schedule can be followed --> Therefore, the approach is to make sure, that there are always enough formwork elements on site, to meet the estimated demand + some buffer --> Leads to a lot of waste in space and rent on the construction site --> Especially elements taking up valuable space on site is heavily impacting the productivity and safety on site - Formwork elements which are currently not used are stored in some corner on site and when the item is needed again, the workers might have forgotten where it is and have to look for it or simply order a new form --> Missing transparency is creating these issues - The better and earlier TCI planning is integrated into a project, the better the site planning can benefit from the transparency regarding TCI utilization and save money and time on site	**Contractor 4**
1	**General Validation of the Solution**	
1	What is your first impression after the presentation of the prototype solution? From your perspective, where do you see the most potential in the proposed solution, integrating TCI planning and management in the existing BIM-based project delivery?	
	- Easy accessible for people who actually use the data --> mobile app for site workers and dashboard for management - Challenge: Difficult to automate the process of formwork planning as it is a quite heavy engine with many complex considerations --> Make an option to manually plan the complex parts of the project as the automatic planning is best for easy wall layouts - Also consider the impact of changes to the system --> address how changes can be implemented in the TCI utilization plan --> Implement changes in an easy way! --> all changes has to be done in the schedule to update the TCI utilization plan!! - A lot of benefits of this tool for the industry - **Main benefit**: Large amount of easily and automatically calculated formwork elements (for big in-situ projects with straight walls and rectangular corners) to plan all tasks in advance and just instruct the workers with the assembly of the already correctly located items - Formwork elements itself are not expensive. But the installation and handling of formwork elements can constitute high costs and are mainly affected by the transparency and available information --> The solution provides transparency for the contractor but also the TCI provider to apply a more lean and efficient management of formwork elements - Information about which items are available at the job site or what is the pool of material available.	**TCI Provider 1**
	- Solution is very interesting and has a lot of potential to increase awareness and transparency of the utilization of TCIs - Interesting to actually use it in a construction project and make the workers actually use it and benefit from it - Construction Management will benefit a lot and gain **control** over the TCI utilization --> Better planning of the site logistics and space management --> Continuous construction flow with a forward-looking and lean approach - Benefits range from reducing waste, gaining more space on site and reducing costs as all in-situ concrete related construction activities can be executed in a more efficient and secure manner - Also environment gains on the solution as only the elements are ordered which are actually needed and waste is highly reduced --> environmentally friendly	**Contractor 1**
	- Interesting solution, but based on a lot of assumptions (cost information, only straight walls) - Need for a process flow where and when is the solution used in a construction site	**Contractor 2**
	- Good first impression - Easy and understandable process --> Main potential with the site integration that people on site will directly use and benefit form the solution and can give their feedback to the project management level - Having transparency which enables just-in-time delivery and a dynamic consideration of TCIs benefits a contractor	**Contractor 3**

Findings from Evaluation Interviews (Chapter 6)		*red = comment
No.	**Question**	**Interviewee**
	- Fascinating solution that tries to solve a real and complex problem in the construction industry with an open standard approach - Extremely usable solution for contractors	**Consultant 2**
	- On the right track with the idea and developed solution - Automatic generation of TCI utilization is targeting a niche in construction which is not yet fully optimized	**Consultant 3**
	- Good first impression and solution looks very promising and nice - Generally scared when something is automated when it comes to quantities --> Really need to be sure, that whatever you extract from the different sources is valid --> possible solutions: 1. Developed standards which the stakeholder have to follow to guarantee the right data 2. Create model checks to verify the model according to the specifications (e.g. clash detection according to the ICT agreement --> Need to establish a verification process of what is extracted from the BIM data (model & schedule) - Generally on a construction site or any production site (also in factory), it is important to know where stuff is --> Solution targets this need and thus provides a great value --> Knowledge about where equipment is lying and how much of it is on site and where it is used next. - It is really showing the potential of integrating data sources in the construction industry which historically has been really poor --> Currently it's a problem of chicken and eggs because people don't structure the data because nobody uses it, so why do it. --> Therefore, there is a risk that the data is not correct and this requires some awareness and quality assurance means to assure the data integrity --> With standardization and generally a higher technology level of the industry, this can be resolved in the future - Lean management is currently not possible because the information is missing. The proposed solution provides this information and therefore, allows to have a lean management --> However, it requires a **change management** in the way people work and this is a fundamental part of the thesis! --> Emphasize in the thesis project that the solution provides the information and potential for lean management, but there is a lot more needed to actually implement a lean management process on the construction sites --> not just technology (emphasize this in the thesis) - Thesis intention should not be to develop an intelligent engine to calculate formwork elements, but rather provide an idea or platform of connecting things (--> be specific about that in the thesis goal)	**Consultant 4**
	- Cool approach to take the standard data from a building model and use it to calculate the quantities of items which are in a relation to the extracted building elements --> Can be applied to many different areas (e.g. sizing of a radiator, thickness of a slab and the division in hollow core elements) --> approach to create a data model to each project and use it for calculations has a big potential - Use of a very generic perspective (data modelling with Linked Data) on a very narrow problem (formwork planning & management)	**Consultant 5**
	- Good first impression of the solution, integrating the available data and going through the entire process but applying it to one specific area (TCI utilization of formwork) and **bringing the BIM data to the construction site !** --> Deeply into the data of construction --> Maybe too deep to where the construction projects are today - Good corner that has not yet been touched and therefore provide value to the industry! - Similar to the process of managing prefabricated elements (certain order, just in time) but including a calculation engine to provide the TCI information	**Consultant 6**
	- Impressed of the holistic scope of the project --> Managed to link all the relevant data (building, schedule and TCI data) into one solution and create a functional and automated process flow to generate the desired result - Sees the need for such a solution in the industry, however, not sure if all the contractors are already ready for this	**Consultant 7**
	- first impression of the proposed solution is that it is a good concept with a lot of potential for further development. It gives the management team as well as the contractor a good idea what TCIs to expect in the upcoming period as well of the expenses which come along.	**Client 1**
	- Good first impression and appreciates the data-driven perspective with using an open data environment and data model to generate value for the construction site - Main benefit would be the saving that are generated by the dynamic stock consideration with reduced items on site leading to less rent and less waste of valuable storage space - The second biggest benefit is the enabling of a lean management due to the transparent TCI utilization plan --> Has to be integrated into site planning	**Contractor 4**
2	What are the benefits of the proposed solution? Can you name the benefits for each of the following stakeholder group? Who else might benefit?	
	Everyone will benefit from it. --> reduction of amount of deliveries to and from the site --> cost savings for everyone (also due to reduction of waste) **1. Client:** - Reliability of the contractors offer, less claims and more transparent construction site, able to follow the schedule without cost and time overruns - Easily apply the solution with different provider and find the best fit/ price for subcontracting a supplier (same for contractor) --> comparison between suppliers with proposed solution **2. Contractor/ CM:** - cost savings due to reduction of waste, more efficient space management on site, more efficient handling of TCIs and less waste of time - citation form contractor at case study site: "Soon I'll be running out of space on the job site to put the formwork. Where shall I put the formwork?" --> If he can plan it better, he could store the forms somewhere else when they are not needed (external stock) and he knows exactly when to bring it back but right now as he does not have the complete overview over the formwork utilization, he needs to have everything available nearby --> taking up a lot of space for storing but also cost and time for handling --> need to move the things around on the crane on limited site often as the construction site evolves --> time and cost increase - Could create a small stock yard for the site to store all elements which are not immediately needed but the contractor would know exactly when which items are needed from where on the stock yard to where on site - proactive consideration of TCIs, less reliability on supplier **3. TCI Provider**: - For supplier, a better planning of the construction site from the contractor always also means a better planning for the supplier - Better and forward-looking planning of the own stock yard --> Less overstock due to transparent information how many elements are needed when on which project - More time for design engineers to focus on the complex and more important formwork constellations on the project - If the solution is used in-house: Easy calculated offer for standard and simple wall structures!	**TCI Provider 1**
	1. Client: - Benefit generally from a better overview and transparency of the project --> Can rely more on the calculation/ offer of the contractor as it is not only based on estimation --> Less extra price claims, finishing on time, less cost overruns 2. Contractor/ CM: - See **above** - Can use it in the bidding phase for formwork supplier to get a first overview of how much formwork would be needed on site to then select a supplier 3. TCI Provider: - See **PERI**	**Contractor 1**
	Not answered	**Contractor 2**
	- Same as PERI - **Client**: Get a better value project with less cost and time overruns --> more reliability	**Contractor 3**

Findings from Evaluation Interviews (Chapter 6)		*red = comment
No.	Question	Interviewee
	1. **Client**: - No direct benefit, but will have more reliability in the estimation of the project both cost and time-wise 2. **Contractor/ CM**: - Cost & Time savings, overview and control over the TCI utilization, potential to optimize the management of TCIs - Active monitoring would further strengthen the solution as elements on site get lost or are used for tasks they are not supposed to be used. 3. T**CI Provide**r: - Could offer the solution as their own service and calculate the TCI needs for their clients (contractor) and therefore can also optimize their own stock and product management - Higher per unit/cost but lower total prize in bid, as a project specific TCI utilization is offered which requires less TCIs - Get more involved in the project and provide a knowledge-based and collaborative service to the contractor	**Consultant 2**
	1. **Clien**t: - Will get indirect benefit from a better project 2. **Contractor/ CM**: - Solution generates value for the party who pays for the TCIs 3. **TCI Provider**: - Both perspectives that the TCI provider benefits from the better transparency of the contractor to order what is actually needed but also reducing the amount of TCIs needed on site, meaning lower revenues per item for the TCI provider per project	**Consultant 3**
	1. **Clien**t: - Will get indirect benefit from a better project --> Reducing risk and uncertainty in a project (extremely important!) - Getting a more accurate price from the contractor (from the equipment management budget) - Especially if the solution is further developed to also include scaffolding and safety barriers, the client would benefit from a safer construction site --> but also the consideration of formwork will give the client a safer and more efficient construction project - Client required the project parties to plan the project in a good way and such a solution would guarantee a good site planning - Client could require such a solution in a project if it is available on the market to see early consideration of the TCI planning and site logistics management in pre-design - It also allows to meet safety requirements from authorities in dense areas a NYC, where a scaffolding is required --> Client can assure to meet the safety regulations with actual numbers and also provide the authority with more transparency to ease the project approval process 2. **Contractor/ CM**: - Main benefits of the solution are for the contractor --> Allows optimize the whole production flow and to have a more efficient and lean management process of TCIs --> Cost and time savings due to transparency - Early stage assessment ! --> Right now, a huge amount of money is put aside for the site equipment management because contractor don't have the knowledge of what items are needed when on site (--> Interesting to ask a contractor how much budget they put aside for that in the beginning and how this budget actually matches out when they go into construction) --> There is a huge discrepancy there - Huge potential in improving the site logistics management with this information (either do it internally of employ a third party as Ajos who takes care of that) --> Requires a further development of the solution with site logistic optimization considerations 3. **TCI Provider**: - First mover benefit --> If one provide would offer this automated calculation, he could reduce his costs and therefore provide a cheaper offer	**Consultant 4**
	1. Client: - efficient project as a side effect --> But would also get more security and minimized project risk as he could require the contractor to proof that he has some consideration regarding the work environment on site --> Can provide clear and transparent information with the proposed solution --> Tailor made dashboard for client mindset would also add value to the client **2. Contractor/ CM: - Can automatically get information of the TCI utilization on site and thus, can better plan the site layout and logistics as well as workflows** **- transparency of the project and optimization of workflows in general** **3. TCI Provider: - More transparency and better collaboration to the projects** **- Can be directly integrated into the project, giving advice for the design and planning as well as calculate the TCI demands** **- As the TCI provider can give a detailed offer based on the building model, the offer is also not only evaluated by the cost per item, but rather by the cost impact on the whole construction project --> Supplier with higher item costs, but a much better workflow and system would end up winning the contract, as the project manager has the transparency to compare different offers on a much higher level of detail (over time and impact on site)**	**Consultant 5**
	- Who will benefit the most generally depends a lot on the business model, who is in control of the data model and who is providing the data for whom 1. **Client**: - Benefits indirectly of the more transparent and reliable construction process --> maybe gets a discount as the contractor can better plan the construction project - More focus on safety on the construction site through the detailed TCI information on a task level 2. **Contractor/ CM**: - Positive impact in the site logistics and layout planning - Lowering the stock and storage demands on site through a more dynamic and just-in-time delivery - Big contractors with the whole production within their organization can overtake the data model from the design team and have then full control over the construction process with all PCIs and TCIs planned and managed through the structured project data --> Close solution for one company only 3. **TCI Provider**: - Can better plan his stock with transparent information from sit - Can integrate his expertise earlier into the project if he takes an active role in this approach	**Consultant 6**
	1. Client: - More certainty that the project is delivered on time - More safety awareness and consideration on site --> Less items and a better planning on site = safe construction site --> client might end up with smaller construction site **2. Contractor/ CM**: - Reduce unnecessarily blocked space on site - Reducing time and costs of TCIs (in different process aspects as rent, logistics, storage, installation, dismantling) - control and transparency about the TCI utilization leads to a better planning and management of the site workflow - Higher certainty that the amount of items on site is sufficient to meet the TCI demand, but the TCI management is also efficient and lean in the same time **3. TCI Provider:** - Depending on the business model, the created value of the solution might interfere with the interests of the TCI provider as they want to maximize the amount of items, they rent out to the construction site --> In contrast to what PERI says! - If solution is used by supplier, they can offer a better and more transparent service to the contractor --> More competitive price as less items have to be used on each project and they don't need to have an overstock in their storage --> Can use saved items on another site or also temporarily exchange items from construction sites as the transparent handling allows it	**Consultant 7**
	- Both contractor and the client management team will benefit from an automatically created TCI plan. For the contractor it can be reminder of what is needed. With the reminder he can do a quick calculation of the quantities just to ensure that the amount provided matches the TCI plan. As for the management team, a TCI plan provides a good indication what to expect and plan the economy in accordance to it.	**Client 1**
	1. Client: - No direct benefits **2. Contractor/ CM:** - Benefits the most from the automatically generated TCI utilization plan providing transparency to better plan the construction site and use a dynamic TCI delivery approach which results in less waste of space and money **3. TCI Provider**: - From the first perspective, do not benefit from the solution as TCI provider generally make a lot of money due to the fact that the contractor does not know his TCI demand on site - On the second perspective, the TCI provider can improve the communication with the contractor who can order the precise amount of TCIs in advance, leading to a better stock planning of the TCI provider who can reduce the amount of formwork elements	**Contractor 4**

Findings from Evaluation Interviews (Chapter 6)

*red = comment

No.	Question	Interviewee
3	By integrating TCI planning and management into the construction process, the proposed solution aims to improve productivity and safety on site. In what extent do you see this intention fulfilled? What would be required to solve both issues with the proposed solution?	
	- Safety generally as a secondary effect of a better and more transparent planning and management of TCIs - If specific safety measures are applied: (1) all items in the formwork process have to be considered, (2) add direct safety means to increase safety --> SRF with notification, assembly procedure with video or pdf instructions, checklists for each task which TCIs are there and what is missing - Productivity is obvious due to more transparently and lean management of TCIs	**TCI Provider 1**
	- Agreement - **Productivity**: Much more **control** over what to order and when, just-in-time delivery, more space available on site, improved logistic on site - Security that the utilization plan is correct leads to less contingency in estimations, safe cost - Visualizations are important to increase safety --> Model TCIs in site model or use visualizations/ videos to show assembly procedure and risky activities - **Safety**: More space, better handling of site materials (less material flying around) and SRF raises awareness if used correctly and based on experience. Further improvements should be a video or visualization that shows the specific assembly instructions of each activity, a 4D site model that allows the worker to review the digital twin and also allows a safety professional to analyse the process digitally and thus, prevent accidents.	**Contractor 1**
	- Need to conduct case studies on projects to quantify the benefit of how much improved productivity and how much more safety is realized on site with the use of the proposed solution --> **Field work:** Follow a production crew who construct a in-situ wall without the solution and then compare the same process with the support of the proposed solution!	**Contractor 2**
	- Solution has to cope with changes which happen all the time on a construction site --> Now, changes are only based on schedule updating through the progress monitoring. Would be nice to also make the solution write back to the model and update the model to as-built. - When you know your production and can plan ahead, the safety and productivity is increased as well	**Contractor 3**
	- Better planning and transparency automatically improves productivity and safety - More a secondary effect but cost savings can be seen directly - Especially the lean aspect supports the improvement of the productivity on site - With knowledge about what has to be installed where, safety instructions and risk factors can be introduced to the specific tasks to raise the awareness of correct execution of tasks and safety	**Consultant 2**
	- Saving time and money for the contractor and increasing the efficiency on site and therefore also increasing the productivity - SRF + assembly instructions per task are increasing safety	**Consultant 3**
	- Yes - With safety consideration as a SRF and especially assembly instructions for the construction workers, safety is improved on site - Calc Engine can be used to calculate scaffolding and safety barriers and by that highly increase the safety consideration on site --> Especially for contractor, this would provide great value to their responsibility as the consideration is automated --> Also important from a client perspective to have safe sites and provide transparency about the safety considerations! - Productivity improvements are a result of the possibility to better plan and manage the construction site due to the TCI utilization plan and the transparency it provides - Improves productivity if it calculates the right thing --> Data integrity	**Consultant 4**
	Yes, valid assumption	**Consultant 5**
	- Difficult to get a better safety as the construction workers need to use a mobile application --> Giving them insights of each task --> Maybe foreman needs to be in charge to show the workers the assembly instructions for each task! - Safety as a secondary benefit from more transparency on site and a better workflow with less formwork lying around - Productivity improvement due to transparency and better planning and management of the site --> also just-in-time and less stock needs	**Consultant 6**
	- Yes	**Consultant 7**
	Not asked	**Client 1**
	- Productivity absolutely - Safety also, but more as a secondary effect --> If including the assembly instructions and the safety risk factor (mark tasks in green, yellow and red to identify risky tasks!) --> Huge improvement in safety can be generated as less items are lying around the construction site and if the TCI utilization plan is further integrated into the site planning!	**Contractor 4**

Findings from Evaluation Interviews (Chapter 6)		*red = comment
No.	**Question**	**Interviewee**
2	**Improvements/ Further Development**	
4	Would you and how would you use the proposed solution in one of your projects? What further development/ considerations are needed to apply the solution in a real construction project?	
	- Use of the all items in the formwork process to develop a holistic solution --> Corner, Wall endings, platforms, safety guards etc. (Otherwise, contractor won't buy the solution and will just be another tool in the box that he will not use) - Include man hours of each task related to the formwork application --> time and economy --> Try to quantify the benefit of the solution by integrating the tasks which account for the biggest costs (handling of formwork on site and not material costs) - Include curing time for concrete that depends on the geometry and characteristics of the concrete as well as the weather conditions on site - Include cycle plan of the contractor, when which wall will be installed --> Information for planning corner elements and wall endings with waler and plywood) - Focus on the data integration and distribution part in the solution and outsource the TCI calculation (to supplier) - Link the logistics status with the database, to know how many items are actually currently on site and when the next ones are delivered --> What is delivered and what is returned?? --> PERI would use the solution by asking the client (contractor) to use it and therefore get a better planning of the items subject of delivery	**TCI Provider 1**
	- Would use the solution in a small pilot project to test its functionality and to get feedback from the workers who will use it - Using default TCI dataset is good in the beginning to get a first estimation and to compare bids of potential suppliers. --> Gives a quantity without already choosing a supplier. If supplier provide or publish their products, a cost and time comparison of different product solutions can be made easily. - Link the logistics status with the database, to know how many items are actually currently on site and when the next ones are delivered --> use exicute as a communication platform for the supplier? - Dependency/ Reliability to what is planned automatically --> what is planned has to be executed --> little flexibility for the site workers to improvise --> construction workers are used to get a big box of material and then they look what fits and apply it (as playing with a box of Lego) --> if everything is planned, the workers have to follow the plan and the plan ahs to be easily understandable for the workers! - Needs to be open for different BIM modelling and scheduling software - Integration of 2D-calculation, 4D-site modelling, different TCIs - Prototype is good, but is only a first test and had to be further developed by testing in real life and asking persons who would directly benefit from it, for feedback and improvements	**Contractor 1**
	- Focus more on the collaboration aspect from the construction workers with the project manager --> Construction worker will check on checklist if they installed all TCIs for the construction task and PM will get the update on the dashboard - '- Eliminate the number of ideas and uncertainties around the solution and create a connection to reality --> Only a prototype that has to be tested and applied to a small production activity where the real benefits can be quantified --> Small scale on task level: if the solution can't provide benefit to the task, it won't give benefit to the project - Not possible to name any benefits without the proof of functionality of the solution - Need for flexibly change the master plan with the current circumstances on a construction site - Consideration of the technology demand of small contractor --> Can use solution with the help of a consultant! - Consider the balance between optimizing safety and productivity --> Solution only raises the awareness of safety and improves the space management and reduces safety hazards as the construction and logistic processes are transparently planned	**Contractor 2**
	Not answered	**Contractor 3**
	- Yes, but - Solution has to work with all the different software applications and all stakeholder who might not be on the required technology level --> Create ontologies for describing each data source (model, schedule and TCI ontology!) --> Data has to come from different stakeholder (engineers but also supplier) and therefore, must be directly published in the right format or converted - Solution must be extended to cover different data sources in the following three areas: 1. Software applications for the BIM data, 2. multiple TCI types (not only formwork), 3. multiple products from several supplier --> Decision to create a specialized solution or a platform solution that can generate utilization plans for multiple TCIs from multiple data sources - Solution helps to get an automatic planning of TCIs that enable an efficient management of TCIs on site --> Next step would be to optimize the storage and logistic management with the generated data! --> digital integration of an logistic optimization tool - Write back TCI utilization data to schedule and model and try out different scenarios (e.g. with AI) for optimizing the project delivery --> Avoid special formwork elements, reduce amount of formwork sizes, adjust schedule according to TCI information (requirements, availability, etc.)	**Consultant 2**
	- BIM part is making the solution difficult as not all stakeholders who are involved in the process can provide their data digitally - Important to also work with some manual input for providing the information - Need to answer the question how much of the solution can be done without BIM --> Take the target users from the level of technology where they are today --> Flexible solution - Develop a stable and final solution where all shortcomings and uncertainties are considered and eliminated and everything works as expected - Solution focuses mainly on planning part and only provides raw information for a better logistics and storage management of TCIs on side --> Further Development would be to focus more on the logistics planning with the transparency that is provided by the TCI utilization plan	**Consultant 3**

Findings from Evaluation Interviews (Chapter 6)		*red = comment
No.	**Question**	**Interviewee**
	- Solution depends on the data integrity of the extracted or received data from the different stakeholder --> For full functionality, require standardization and digitalization in the construction industry --> Use some manual input in the solution for parts which cannot be received automatically - Intermediate step of the solution could be a semi automated linking of the data ad if the data quality is assured, a fully automated process can be applied in the project - Passive progress monitoring requires the construction workers to actively track their work and what items they used via a mobile application --> Requires a change management to implement it on site --> Active tracking with IoT-sensors would allow to actively track the items on site without the need that construction workers have to actively monitor their work - Consider a packaging service from the TCI supplier or Site manager --> With the information of what items are required where on site, a responsible party (also as Ajos) could set up and locate all the items which are needed for each construction activity on the location, where they are needed --> extra service for site logistics manager --> Would allow a lean management with an efficient space utilization and construction flow on site and reduced waste in terms of material, time and space - At TNO in holland, they had this concept of **BIM bots** --> The idea is what you have small tools like your formwork calculation engine. But you could have any kind of tool and it could be PERI to provide a engine for formwork design and it could be the safety barrier provider, to provide an engine for their project expertise --> Fits well into the idea of a Linked Data environment where different stakeholder publish their project input which can be used for improving the project --> e.g. A formwork design and utilization plan can be provided from PERI and the site manager can use this information for developing a lean site & logistics process that also gives feedback to and can optimize the project schedule - No matter how many bots you include in the system architecture, the solution would still work --> Will never create a solution that can do everything, so the more generic the middle part of the solution is, the better it is --> **Data management/ processing** - Would be great to establish an infrastructure for stakeholder integration so they would provide the project with the required input, based on their products - If the solution can also provide feedback to the planner (model and schedule) as well as to the site planner --> optimization of model, schedule and site logistics based on the calculated TCI information --> Full integration in the construction process, creating a lean --> NCC's Efficient Logistics project --> a lot of planning of all the materials that are needed on site (similar consideration!)	**Consultant 4**
	- TCI supplier could act as service provider to the project, getting access to specific data in the data model to calculate their TCI demand for the project and link it to the project data model from where the project manager can use the information to design the site layout and workflow --> Supplier can be included to the project and give their expertise regarding the project planning with some suggestions of changes in the project that would reduce the costs of TCIs (especially handling) and then also easier provide their offer within a functional tender - Solution can be further developed to the planning of the site and logistics management as now, it is only providing the raw data of how much is needed where, but doesn't suggest where it has to be stored before and after use --> assembly instructions would already --> Flow on the construction site to be integrated: Where is the stock, how are the items moved from one part of the construction site to another part --> Shift the transparency not only to what is needed but also to how this will work in sequential order between (local) storage to use and back --> break down the process of applying formwork to the different steps - Integration of the solution into a digital construction site planning (4D)	**Consultant 5**
	- Structured data in the construction projects with data model consideration and standardization how to describe and model the data is required to make it work --> Only few contractor today have control over their data --> But this will 100% evolve in the future --> Otherwise a third party is needed who will modify the data from the stakeholders, so it can be used for the Linked Data environment - Integration of different stakeholder into a project is only possible with the standardization of data	**Consultant 6**
	- Not sure if all contractors are already ready for the solution, as it requires structured BIM data for the whole project --> Solution depends on the input of the different stakeholder in the construction chain and thus requires a certain level of technology of all the stakeholder - Improve the formwork calculation engine with more advanced algorithms and different TCI types - Also open up solution to also add data manually which is not covered and not part of the system --> Fully automatic solution might not be able to cover all geometries and complexity of structures --> If the solution solves 80% of the problem, but it takes 80% to solve the last 20% of the problem, then there is an issue for implementing the solution in real life - Apply the solution in a pilot project and determine and reduce most of the uncertainties and clearly demonstrate the benefit of the solution to convince also the conservative construction industry that this is actually beneficial - Solution is only working with Revit models --> Standardized solutions as ifc-models would be better to reduce the dependency to a software --> Either have a solution that uses standardized data sources (model, schedule) or make the software applications automatically extract the data as Linked Data (in RDF triplets) that the individual generators of the data can publish it directly to the Linked Data project environment	**Consultant 7**
	- Deploy the proposed solution on the project with the considerations of theory and practice, as well as taking bugs into account. Because theory and practice never go hand in hand. As this concept is quite new it needs to be employed in small projects first to see how it goes.	**Client 1**
	- Difficult to implement such a solution in the current industry as it requires an effort regarding change management to change the way people work --> Current practice is very slow and inefficient with information management from the construction site using change orders, etc. A simple information registration from the worker on site in a mobile application would generally improve this information management a lot but it is still not implemented widely --> Using data in construction is a quite new approach and the industry has to adapt to it, in order to fully implement such solutions --> The more visual and easier the solution is to use and understand, the better it can be implemented! As simple as possible to provide the required information - Enhance the impact to design by giving feedback to assess the TCI demand as early as possible in real time when the building is modelled --> e.g. include a real time engine in a modelling software that provides the formwork quantities for each modelled building element as it is modelled, hence, adding the TCI consideration as a new design factor e.g. maximize the number of standardized formwork elements! - Also include slabs, columns, beams in the formwork calculation engine --> catalogue of items will be quite big to create a holistic formwork calculation within one solution - Extend the solution to include also other TCIs! - Further utilize the output of the proposed solution and integrate it into the site planning and lean management process of the construction site --> Using QR-codes to enable this integration as it requires to know, where the items are (e.g. integrating it into IRIS cloud platform)	**Contractor 4**

Findings from Evaluation Interviews (Chapter 6)	*red = comment	
No.	**Question**	**Interviewee**
5	**Step 1 - Data Sources & Extraction:** Do you see any obstacles in the way, the BIM-data is now extracted from a project? What modifications are needed to apply this step in a real construction project?	
	- Formwork dataset has to consider all items that are needed in the process of constructing in-situ walls (pouring platforms, wall endings) --> Data has to be complete in order to apply it on a real project! - Revit model has to be modified by contractor in order to model walls as they will be constructed --> Or client already requires the architect to model the building model as it will be constructed	**TCI Provider 1**
	- Open solution that works with multiple BIM software applications or open BIM standards as IFC	**Contractor 1**
	- BIM models are modelled differently and the solution should be able to flexibly handle variances in the BIM model --> Either put it clearly in the ICT agreement how the model must look like or create adjustment possibilities of the solution - Property extraction from the model can be difficult as a wall length is not always the wall length of the real wall --> Solution must extract the right data and must do that for all different software application used in the industry	**Contractor 2**
	Not asked	**Contractor 3**
	- Develop standardized ontologies that describe the different data sources (building model, schedule & TCIs), so that all stakeholder can publish their input in the right format and make it accessible - Include different software applications as data sources in this solution which are used in the industry	**Consultant 2**
	- General contractor is responsible for planning, Arch./ Eng. is responsible for building model - More open/generic (ifc-based) data extraction from the building model --> Not based on software application --> Or simple excel import?? - Focus on more elements than formwork in the TCI ontology --> Where else is a need for a utilization plan? --> Cranes, scaffolding, ladders, supports, etc. - Concept that allows also to use machines and other TCIs with the consideration of how they are provided --> Distinct process of storage and delivery if the items are owned or rented! --> Internal rental store or external rental store	**Consultant 3**
	- Using open API to extract the data would probably be easier to apply the solution in the current industry than Linked Data - Quantity extraction from a building model is risky as it requires a correct model setup --> a more open and standardized (maybe ifc-based) data extraction might solve this issue to reduce the risk of false quantities due to an inaccurate modelling --> also ICT-agreement - Creating standardized ontologies for the supplier data --> Standardized ontology framework for the construction industry. - For scaffolding and other TCIs, maybe more data is needed (load considerations) which has to be integrated as well	**Consultant 4**
	- Solution can also be done with usual data integration and the use of open APIs --> Linked data is one approach to do it and a way of working that opens up the process to different stakeholder who could add their information to the project --> Creation of a standardized approach as you give the suppliers a standardized language (ontologies) to describe their products and as a project manager, you can use this data in combination with all other datasets from the project - Parse model data directly from Revit into RDF triples (not through Dynamo) or even from a standardized model format IFC. --> In the future, you want the BIM authoring tools to directly communicate with the data store of the data model - Automated rule-based checking of the quality of the data sources (in LD via SHACL) to see if the individual data model complies with the requirements --> Could develop a dashboard to report the warnings back to the modeler, so the model gets modified accordingly to ensure the quality of the data sources and the security of the correctness of the output	**Consultant 5**
	- As data in construction projects is not good enough, a party has to adjust or modify the data first (great effort) or establish a QA tool that assesses the data from the stakeholder before it is used for the Linked Data Environment - Integrated solution allows to validate the data which is coming in, but many stakeholder are also restrictive in using integrated solution as they fear that it can automate the whole process	**Consultant 6**
	- Open for other software applications --> More standardized ifc-Approach possible	**Consultant 7**
	Not asked	**Client 1**
	Not asked	**Contractor 4**
6	**Step 2 - Data Management:** Do you see any obstacles in the way, the data from different sources is now stored & managed as Linked Data in a triple store? What are the requirements for a Linked Data environment for a project?	
	- Might be a challenge to introduce Linked Data to the construction industry and require all stakeholder to contribute --> Existing project information sharing environments as byggeweb are already in use and it is difficult to introduce a new solution --> Keep it in one place! Link to byggeweb?? - Implement it in the environments the stakeholder already use --> Get data from Byggeweb for example as the ideal current scenario --> Require all involved parties to publish their work in Linked Data as a future vision (name benefits of linked data!)	**TCI Provider 1**
	Not asked	**Contractor 1**
	Not asked	**Contractor 2**
	Not asked	**Contractor 3**
	- Right approach to use an open data format as Linked Data that can disrupt the industry and improve collaboration - Standardization means are needed to develop a framework in which the stakeholder can publish their project specific input - Right approach to create a flexible platform that pushes the data generation and distribution responsibility towards the supplier and then pulls the required data to create value for the project - For the consideration of creating a commercial product, the Linked Data approach is too futuristic and can be replaced by a simpler API-approach with classic data integration	**Consultant 2**

Findings from Evaluation Interviews (Chapter 6)

*red = comment

No.	Question	Interviewee
	- Use of Linked data required standardization for data extraction and management based on standard ontologies which are able to describe the full context of the process - Linked Data is only one possibility to use such a solution and Triplets are only a way of specifying objects, its properties and describing their relationships --> So far, only ifc-Ontology is working properly in the construction industry - Difficult to classify such a complex context as the built environment and its project delivery - For a business case, there would be more potential to just use an open API of the data providers without the need to translate everything into RDF language and create Linked Data ontologies - Linked Data challenges: - Safety and privacy of data sharing and also change management and revisions --> Quality assurance process or approval process is needed to make sure the right version of the data is used for providing information for the site logistics --> Only what is approved can be used for this consideration	**Consultant 3**
	Not answered	**Consultant 4**
	Not answered	**Consultant 5**
	- Like the idea of using Linked Data and integrating it in a holistic and functioning approach to the existing process of project delivery --> Keep in mind that some individual interests of stakeholder will be broken by interlinking the data and automatically deriving information --> New roles and responsibilities will arise in the market and we need to go in this direction of getting better data - Need to keep control over the process of what data is used and if the data has the required quality and how the data is processed to get information that benefits the process	**Consultant 6**
	- Team up with TCI supplier and let them use their specialty to calculate the demands of their product in the applied construction project --> Either tailor-make the solution for one specific product only or outsource the calculation engine	**Consultant 7**
	Not asked	**Client 1**
	Not asked	**Contractor 4**
7	**Step 3 - Data Processing & Querying:** Do you see any obstacles in the way, the data is used to provide all needed information to create a TCI utilization plan? What modifications are needed to apply this step in a real construction project?	
	- Outsource calculation of formwork elements for complex structures to specialists from formwork provider --> Link the BIM data to a already existing online calculating program (as PERI Quicksolve) --> only select simple structures (straight walls with 90 degree corners) for applying the solution and let specialists focus on the complex parts and calculate it manually --> Filter options to only select the simple walls and mark the walls thar have to be calculated manually --> Differentiation - Distance developed solution from formwork calculation programs --> Potential lies on the automatic consideration and management of TCIs - Integrate the TCI calculation with the schedule information to consider the working sequence of the walls and include the wall endings. Include detailed information about installation, stripping and dismantling time of each formwork related construction activity - Formwork costs are little, money is spent on man hours and handling effort --> How much time is spent to handle the formwork? Man hours, crane hour, stripping time as a function of the wall geometry, the concrete, the season, the weather --> For how long are the forms in use until they can be reused? Time of formwork in use.	**TCI Provider 1**
	Not asked	**Contractor 1**
	- Must consider a solution for calculating the TCIs for complex structures	**Contractor 2**
	Not asked	**Contractor 3**
	- Would require more services from supplier and other project stakeholder which generate optimization with their specific product for the project and provide the	**Consultant 2**
	- TCI calculation part of the solution should be part of the package! - Make solution more usable for users: 1. User can type in some numbers without the automatic TCI planning 2. Automatic calculation of some TCIs 3. Introduce some visual programming for building the rules for the calculation --> From formwork vendor perspective - 2D consideration	**Consultant 3**
	- Need to be a pretty intelligent calculation engine to cover the whole context of formwork design no matter how complex the structure is - Better to use integration of BIM bots (= stakeholder specific engines that would calculate the TCI demands for the project) and then write the data back to the database --> The more generic the data processing is, the better! - Although such an automatic solution (also with individual TCI engines) can plan standard situations on a construction site, there must still be a possibility to manually plan and change the plan of more complex situations!	**Consultant 4**
	- Great that the solution only works as a data model and doesn't draw elements into Revit as it is not needed and would only overcomplicate the 3D-model --> Task based information about the TCI quantities and reference through the data model to the TCI type information is enough - Supplier who would provide their service to the data model could have a pre validation of the model to check if all the required measures and geometries are existing to generate the TCIs demand	**Consultant 5**
	- A new angle on this could be to use AI that is assessing the geographically modelled building and directly derives the demand for scaffolding of formwork, based on what is modelled in 3D --> Can totally ignore the parameters of the elements and thus, is not dependent on a standardized data structure --> Sees the AI development faster approaching than the holistic standardization of data in the industry - Outsource the calculation engine to the supplier would benefit the supplier as he gets more involved in the project and he can use an advanced engine that only has to calculate one specific product type where he is an expert at --> Both the contractor and TCI provider benefit from the transparency and better plannability	**Consultant 6**
	No answer	**Consultant 7**
	Not asked	**Client 1**
	Not asked	**Contractor 4**

Findings from Evaluation Interviews (Chapter 6)		*red = comment
No.	**Question**	**Interviewee**
8	**Step 4 - Data Visualization & Distribution:** How can the developed TCI utilization data be visualized to create value on a construction site? The proposed solution allows to display the data both in a linked Power BI-Dashboard as well as the application Exicute. Is this approach reaching all parties in a construction project who can benefit from the developed data?	
	- Add assembly procedures in the mobile app - 3D visualization on the app that the construction workers use to show how the elements are assembled - Every client has their own cost for formwork! --> No list price for formwork --> More important to focus on the handling cost of formwork than only on the material or rent price --> Rent is a easily accessible and visual figure as the price for 1 lite of milk, but it actually only makes a really small amount of the process of handling formwork on a construction site (man hour, crane hour, etc.)	**TCI Provider 1**
	- Can still work even though the TCIs are not modelled in a 4D-site model as Dashboard and mobile app reaches all relevant stakeholder with the right information to improve their work - Good to tailor-make the visualization of the data to the needs of the worker who are benefitting from the information --> dashboard for management, app for construction workers - **Exicute workflow**: Worker marks the completion of a task and should then receive information about the next task where to place the formwork elements --> Further receive a checklist of what task are planned today and the next day including TCI quantities and where the TCIs are currently supposed to be located - Screen with dashboard on site would also give a good overview for the construction teams and the foremen to plan the upcoming days	**Contractor 1**
	- Reaches all parties on site --> workers with application and project manager with dashboard --> PMs demand automated dashboards to control the construction site and receive updated information from the workers --> Worker need to provide the data and feedback from site to embrace the communication to the PM - Simplify the solution to only have one platform for the construction worker and the PM --> publish dashboard in exicute platform!	**Contractor 2**
	- BI dashboards on big screen at the construction site works pretty good in my experience --> for project manager and also for regular construction crew meetings to discuss the upcoming tasks and their TCI requirements (see LPS weekly hustle and Daily meetings) - Mobile application for workers is already in use and can be used to inform/remind the worker directly on the TCI requirements for each task	**Contractor 3**
	- Yes, graphical visualization always helps to distribute information in as easy understandable format to the relevant stakeholder, and both presented solutions address the needs of the target persons (project manager and construction worker)	**Consultant 2**
	- Easy for the user to understand and provides the right data to the right stakeholder - further development could be to include an XML output for directly communicating with an ordering system of a supplier - Click on app to automatically request TCIs	**Consultant 3**
	- Addresses all the stakeholder and provides the required information	**Consultant 4**
	- Addresses the stakeholder and provides the information in a usable format - Solution also allows to flexibly modify the dashboard and create a tailor-made dashboard for another stakeholder who requests information	**Consultant 5**
	- Modelling the TCIs and hand out shop-drawings for the construction workers (as IKEA instructions) would help the workers to get an overview of what is needed where and how to install it --> Auto-generated shop drawings - Otherwise, the two data visualization and distribution means are able to deliver the required information to the construction workers - Dashboard can also be extended to reach the TCI provider who can have a dashboard for each construction project, knowing when to deliver which elements	**Consultant 6**
	- Use augmented reality to compare what is planned to what is installed --> E.g. AR at PERI or Pascal --> 3d-modeling of TCIs and integration in the site model --> model has to be aligned to the real life --> also for TCI consideration! --> Combination of AR and the automated planning of the presented solution could be very interesting	**Consultant 7**
	TCI data will be valuable if it contains the development of construction site. In other words, it has to adapt to the changes which occur during the construction process. Location, quantities, start time and end time of the use of TCIs. That way you know exactly what is needed, where it is need, when it is need as well as removing it. In the SDU SUND project, the contractors use Exicute to report the progress and complications, if any occur. As for the owners, they can follow the work progress and compare the actual working progress with the theorical schedule. A dashboard is a great tool to have a complete overview of the project, but it contains a lot of data which may lead to a long loading time.	**Client 1**
	- Reaches both the management and construction workers --> Construction workers are getting used to the utilization of mobile apps to report their work - Visualization of the data should be easy to understand also within a short time --> If passing by, the foreman should directly see which TCIs are needed for which tasks --> Gantt diagram with location information and precise TCI quantities would be sufficient for the foreman --> Developed dashboard however, is good to deliver the more detailed information to the management perspective - Safety Risk Factor can be highlighted in each task in green, yellow and red, identifying the risk level of the task regarding the utilization of the TCIs	**Contractor 4**

Findings from Evaluation Interviews (Chapter 6)		*red = comment
No.	**Question**	**Interviewee**
9	The proposed solution is enabling a passive monitoring of TCIs, based on progress information from the construction process. A further development for an active tracking of TCIs is the implementation of IoT-sensors. What is your opinion about this? Is an active tracking necessary for TCIs on a construction site? If yes, how can this technology be implemented in the system architecture?	
	- Difficult as formwork elements are durable, are constantly exposed to high loads, movements and different materials as concrete and steel --> Difficult to install a sensor that withstands this, high risk of breaking the sensors during construction - Would still be too much of an effort for a formwork supplier --> for some preassembled parts, it is already implemented - Sensors would need to be on every item to ensure usability of the tracking system. Not feasible right now and no company currently does that	**TCI Provider 1**
	- Would be the next step to even more increase the transparency and control over the TCI management --> Not only knowledge where the forms are supposed to be, but where they are actually located --> check the workers, security for management that work is being done as planned - Sensors (if integrated robustly in the elements) can also have much more benefits as they would count the use of a form and how many times it can still be reused before disposal	**Contractor 1**
	Not asked	**Contractor 2**
	- IoT-Sensors are used in the company for monitoring what is built and after it is built --> Monitoring water supply, power supply, ventilation --> Improve construction process because real time data is generated about what is going on site - Cheap, easy to use, cloud based --> Big benefits to keep track of the construction process - No use yet for location based IoT-monitoring --> should be possible in theory though!	**Contractor 3**
	- Should be the next step to not only plan the TCI utilization, but have a tool to actively track the items and compare it to the plan --> Possible and cheap technology to use - Active monitoring would further strengthen the solution as elements on site get lost or are used for tasks they are not supposed to be used. - Quality control of the solution implementation with real-time information what is where	**Consultant 2**
	- Technically possible and fairly easy - Better use case for the further development with more focus on logistic management --> Active tracking for more control in this management - NFC tag for checking in and out of storage area on site - Real time site logistics with location consideration by using an antenna (wireless because... --> AR for site) --> possible but more expensive - for logistics consideration cheap tag on the elements is the better choice - counting items with image recognition --> Recognize the size and type of the items on site --> how many items are used/ on site	**Consultant 3**
	- Active tracking would reduce the responsibility of the workers to track their work manually --> Less risk of human failure --> Now the solution relies a lot on people actually reporting back to the database with the mobile app --> Would allow to create a production flow with a sort of fleet management system (instead of cars, TCIs are managed) - IoT itself also has a lot of challenges and limitations (range, damage, etc.), but can be solved in the future - Would definitely improve the reliability and functionality of the solution especially with items that are reused on site multiple times as formwork --> If a dynamic stock with just-in time delivery is chosen and then the workers cannot find the items and there are not enough spare items on site, you are really doomed --> active tracking would reduce the risk of workers not following the plan	**Consultant 4**
	- Would further foster the integration of the solution to the site management --> Where do you store it and check how does it move --> Controlling unit for active site monitoring to check compliance with the plan - IoT-tracking will come and it is so easy to install sensors to TCIs - Linked Data approach provides a framework to include IoT-data into the existing solution	**Consultant 5**
	- Would provide the construction project with automatic feedback on the process with high detail to control the workflow --> Workers might not want to be tracked? --> Need to see the benefit in a more transparent and better workflow - Active tracking should be possible if the hardware is further improving --> Is a good way to have control over the process and get some information out of the chaos on site - More applicable to surveying and controlling from the project manager - Workers should also get insights and benefit from the active tracking, e.g. if a item is not where it is supposed to be, the worker can locate an item of the same type which is located nearby --> Finding benefits for the ones who are getting control is the key to sell it the solution	**Consultant 6**
	No answer	**Consultant 7**
	Not asked	**Client 1**
	- Instead of IoT-sensors, which send location information of the items to the database, the TCIs can be equipped with QR codes, which a foreman can scan --> Prefers this solution as it already addresses the change management and requires to construction workers to actively report heir work, which eventually will have to be implemented in order to improve the communication from the construction site to the management --> Information of where the scanned item is will be directly communicated with e.g. the crane who then knows where to get the item from and where to move it next --> Transparent information due to active TCI tracking through workers reporting their activities --> Would create knowledge where the items are, where they have to be moved, when they are installed and when they ae ready for dismantling --> Requires an active role of the construction worker, tracking the construction workflow --> change management --> However, is seen more efficient and better than using location-based IoT-sensors, as the workers can add much more information in their reporting than only the location (e.g. issues, delay, damage, etc.) - Another consideration would be to use a video or image recognition which is, in real time, analysing the construction site and identifying the different TCI types that are lying around the construction site and where they are located --> Would also give information of where the items are (based on the type)	**Contractor 4**

Findings from Evaluation Interviews (Chapter 6)		*red = comment
No.	**Question**	**Interviewee**
10	Is the prototype solution easily adjustable to create a holistic TCI planning & management tool, not only for formwork but also for other TCIs as scaffolding, supporting structures or fencing? Where do you see obstacles in that?	
	- Look at PERI path for scaffolding as a similar solution that also considers man hours etc. - Solution can also be applied to precast industry for planning and calculating the demand of PushPullProps (supporting the precast elements until they are self-sustaining) --> Big market in Denmark for precast concrete and need to plan the TCIs in this industry! - Separate the planning from the management aspect of the solution --> planning with advanced online tool of supplier (holistic formwork calculation, 2D consideration, ability to use different products, etc.)	**TCI Provider 1**
	- It is interesting and beneficial to try the solution for different TCIs and have more than one feature of the solution - Should work in theory **- Obstacles:** - Get people to use the solution as implementation is difficult --> need to directly sense and be aware of the benefits to change the behaviour --> Frist talk to contractor on site and get their feedback and implement their needs	**Contractor 1**
	- If the data can be extracted similar to the example with formwork, the solution is possible to adapt to other TCIs - As a recommendation, the planning software ALICE might benefit the solution, as its element instance based scheduling allows to schedule optimization with artificial intelligence based on different demands	**Contractor 2**
	Not asked	**Contractor 3**
	- Is definitely possible and depending on which business model is chosen, the solution can be specialized for the calculation of formwork elements or the generalization of calculating different TCI types	**Consultant 2**
	- Seems like the problem is generic --> Therefore, it should be possible - Have a individual rule system for each type of TCI --> Establish a system which applies a individual calculation method to the specific TCI type	**Consultant 3**
	- Problem of lack of information for an efficient and lean construction site & logistics management can be generalized to all items on site --> gypsum walls, fences, safety barriers, formwork etc. --> Location based integration of construction elements is the key for enabling a better management and the solution is addressing exactly this data integration and linking - For safety barriers, the calculation engine only needs to identify an opening and then it can calculate the items - For other equipment it can be done similar - Solution can also be applied for infrastructure projects (bridges, roads) as the consideration TCIs for site planning and managing is sometimes even more important - Example of NCC in crane optimization which relied on the concrete element in the building model (weight, quantity and location of the items to improve the crane layout on site) - Solution would also make sense only for one isolated solution for optimization one TCI type, or only fencing and safety barriers, but it would be better to include as much TCIs as possible (e.g. using the BIM bot principle --> then there wouldn't be any limitations of such a generic platform solution)	**Consultant 4**
	- Yes, the mindset of the solution to use Linked Data in a project will allow to apply it for many different things. It is just a matter to find a stakeholder, who would benefit from something and then you can add this to your portfolio.	**Consultant 5**
	- Solution can be applied to scaffolding, safety barriers and also supporting structures for prefabricated elements - But machines as cranes are more related to where it is located and how far it can reach --> no direct connection to the building model --> Maybe site model? (Specify where possible crane locations are and plan which items have to me moved over time.	**Consultant 6**
	- Yes - Great possibility to use the solution for other items on site (e.g. steel plates for heavy machinery, staircase where you put on certain carpets, etc.) **--> Scalable solution !** --> formwork only one application area for the solution as it allows to integrate the planning and management of much more items through the data-driven approach	**Consultant 7**
	- Agrees and does not see obstacles, but challenges. It is in important in the planning process that everything is planned thoroughly. The same goes with different scenarios. So basically, the planning process will become more tough as the planner has to take more into considerations.	**Client 1**
	- Can be done	**Contractor 4**

Findings from Evaluation Interviews (Chapter 6)		*red = comment
No.	**Question**	**Interviewee**
3	**Business Model**	
11	The ideal future scenario (presentation slide 42) requires an involvement of many different stakeholders in a construction project, to deliver their specific input as linked open data, which will be accessed by a calculation tool. Is this vision realistic in the near future? Why?	
	- **Challenge**: Implementation for the contractors --> for making a change in the industry and sustainably implement the solution, the contractor have to be convinced to take over the solution --> Contractor have the mindset to get a job with a cheap bid (using less people and thus quality) = less planning effort = poor planning - Benefit of the contractor have to be visual --> Now, contractors don't keep track of how much time and resources they spend on TCIs (no comparison possible) --> visualization of the of the improvement of their production and their time and their money --> Comparison between how much time they spend on a conventional project for handling formwork and how much they could save with the proposed solution --> Make pilot project where these measures can be derived (how much does it cost to handle TCIs with and without planning?) - So you would have something to hold it up against, which is maybe not existing. So it would take some time maybe to start with to do some field work of actually tracking how much time do this job site really spend on TCI planning and handling and when they don't plan what does it cost them? Because then you will have something to show them that this you will avoid by doing this. And now I will show you on this project how much money you have saved	**TCI Provider 1**
	- Requirements have to be written in an ICT agreement in order to make every party involved in the project, comply with the requirements - Contractor (as a Design & Built, general contractor) is able to set the requirements and make the subcontractors follow - As client is not always professional, he doesn't know which methods are the best	**Contractor 1**
	Not asked	**Contractor 2**
	- See it as a realistic scenario in a few years - All the data is there and also smaller companies will be able to publish their project input or at least provide the raw data for the engineer to translate it into the Linked Data format - Project delivery should be determined in the ICT agreement and already contain requirements and expertise from the contractor --> For a contractor, it is difficult to demand a specific model quality as the engineers develop the models without the help of a contractor	**Contractor 3**
	- Requires a standardisation process for the required ontologies - BuildingSMART is an institution that will foster the standardisation in this area, but it takes some more time - Industry is definitely aiming towards this scenario	**Consultant 2**
	- Not the linked data, but with an open API the scenario is feasible - Standardizing APIS is exactly the same as in Linked Data - Authentication System	**Consultant 3**
	- Biggest hurdle is to standardize how people name and model things --> If this is in place, the solution and vision could work both with Linked Data and an open API --> For near future, need to integrate possibility to manually put in the data	**Consultant 4**
	- There will be a big question of who is generating and hosting the data graph for the project (consultant, client?) --> Common data environment considerations - Centrally stored data model can be hosted by a client consultant and the different stakeholder would gain access to the parts of the model, they need to provide their service - Now, the proposed data flow is needed as the Linked Data approach is not yet implemented in the industry	**Consultant 5**
	- It is a future vision which needs a lot of effort in standardizing the data which is used in the context of construction --> Very hard to implement a totally open and interlinked solution (risk of not getting the required data quality) as long as there is no 100% clean standard - Need to keep in mind the interests of the different stakeholder, if such a solution wants to be implemented --> Contractor for example, want to benefit from the transparency and control, but do not want to share their information --> e.g. progress information to the client - Consultancy as a service can be offered by the specialized supplier who are consulting the contractor with the utilization of their specific product --> Need to gain access to the data model from the general contractor or a client consultancy --> Supplier can also act as a consultant for early project phases where they can apply their expertise to improve the building design or development of the schedule and site model	**Consultant 6**
	Not asked	**Consultant 7**
	Not asked	**Client 1**
	Not asked	**Contractor 4**
12	Assuming that the proposed solution is offered as a **Consultancy Service**, providing detailed information about the TCI utilization on a construction site. What would be the benefits of this business model? Would you consider paying for this service?	
	- Client: Requires the contractor to use the solution - Contractor: Involve a consultant at the first time to get familiar with the solution and then do it themselves on their responsibility --> Do it in a pilot project and then show benefits from the pilot project to the foremen as a proof of concept --> security that the solution works! --> Foreman often decides to order more formwork based on his experience and estimation --> They have to benefit from the solution! - Less fix cost for the formwork companies because of a better planning of their stock --> might lead to cheaper formwork in general	**TCI Provider 1**
	- Contractor need to have control over the TCI utilization (planning and management) and cannot be fully dependent on a consultant --> sustainable implementation of the solution with forward-looking considerations - Best if it is simple enough that contractor can use it themselves after getting introduced to it in a pilot project with the help of a consultant (e.g. two days a week to get started with the solution) - For small contractor it might be better to outsource the expertise to a consultant	**Contractor 1**
	Not asked	**Contractor 2**
	Not asked	**Contractor 3**

Findings from Evaluation Interviews (Chapter 6) *red = comment		
No.	Question	Interviewee
	- Could be a service aspect of a site & logistics management which use a data-driven approach to optimize the site logistics management either from a external company as Ajos etc. or directly from the contractor --> Services in the industry tend to be not only software applications but always contains a consultancy effort as well --> With that comes also responsibility in the process success - Depending on the business model is chosen, the solution can be specialized for the calculation of formwork elements or the generalization of calculating different TCI types	**Consultant 2**
	- Software solution with training from the software provider	**Consultant 3**
	- Consultant would have to team up with a contractor to adjust the solution to the needs of the contractor --> A only third party service would no make sense, as the consultancy have to use the items the contractor wants and have to align the solution to the processes of the contractor --> otherwise the solution would provide false certainty that something is fixed but in reality look completely different - Consultancy part is the whole picture --> setting up the linked platform (different for each contractor) - also consultancy service for the TCI provider to develop the calculation engines that can receive the data from the platform, calculate the demand for the specific TCI and write the information back to the platform **Different Business Cases:** - For a contractor who has a design&build contract, as they have the whole value chain (designer, consultants, supplier) under them, they are able to control the data flows and easily implement such a solution --> Consultancy as Exigo could support the implementation at a contractor - Client cannot drive the use of such a solution as they do not have enough impact on the value chain --> Could require such a solution that provides transparency about TCIs on site, though - For TCI provider, it would be difficult as they do not have a contractual relation with the data provider (engineers for the model and schedule) and therefore would rely on something they cannot guarantee --> As the BIM bot principle shows, supplier could be integrated into the solution by outsourcing the calculation engine to the supplier. --> would provide a competitive advantage for the TCI provider	**Consultant 4**
	- It's a matter of generating this dataset that it is rich of useful information from the project --> When it is rich, stakeholder can do an analysis of the model and provide quantities or results based on their specific expertise --> Would be a service that they provide - Consultant or even client would be the entity who would manage the data model and provide access to the project parties --> In the construction phase, this could go on to the turnkey contractor, or the consultant would also provide the service for the construction phase as they have the knowledge and expertise on data management --> New role of a consultant that is responsible of the data model and provides access to it - Distributed nature of the project delivery will be the future when the focus will go more towards the data model and not the software solution --> different stakeholder would provide their information as consultancy-as-a-service for a specific part of the project	**Consultant 5**
	- **Contractor**: If the company owns many skilled people who are able to generate the data and have control over it, the contractor can apply such a solution to automate the planning of the site and optimize the construction site layout and workflows --> If contractor has the skills, he would definitely prefer a complete solution for their own where he can have control --> want to make it their process! - **TCI provider**: If the provider can get access to the data model, he can provide the TCI utilization and logistics as a complete service to the contractor --> Are interested in structured data that they can hook on to with our with a catalogue --> Need to gain access to the data and therefore also gets responsibility and risk! - First approach would be that a consultancy is introducing such a solution to the industry and helps the stakeholder to establish the required technology level - **Next step**: When the stakeholder getting more mature, e.g. a general contractor who is responsible for the control and takes the risk can use the solution on their own --> Need to have access to the data model	**Consultant 6**
	- Be aware of the impact of the solution to the different stakeholder --> might require new roles or make existing roles obsolete --> Consider different interests and perspectives of the stakeholders when exploring a business model	**Consultant 7**
	Not asked	**Client 1**
	- Current solution can have a big market for in-situ walls if it is integrated into the construction site planning and lean management - As contractor benefit the most of the solution, they should implement it within their organization --> First as a consultancy service in a pilot project to quantify and verify its success and then incorporate it as their own solution in their processes - In order to pay money for such a solution, people have to be convinced that they can save money with it --> Quantify the benefits in a pilot project!	**Contractor 4**
13	Assuming that the proposed solution is developed as a holistic **Software Solution**, providing detailed information about the TCI utilization on a construction site. What would be the required further developments of the existing prototype and potential obstacles? What are the benefits of this business model? Would you consider buying this software?	
	- Consultancy is more flexible and stakeholder rather outsource what is not their main responsibility or strength (**in contrast to what says Contractor 1**) --> Contractor fear the risk of dependency towards only one provider (PeriCAD is not used by the clients/ contractors) --> Software solution has to be an open solution that is not only applicable with one provider! --> Although it would be cheaper and more efficient for big contractor to plan their formwork themselves by having two specialized employers, doing it for them --> Big contractors have budgets for each project and hiring a consultant can be put in this budget, but buying a software license would go to another pot of expenses	**TCI Provider 1**
	- Solution must be flexible and simple enough that a contractor with enough resources can use it alone	**Contractor 1**
	Not asked	**Contractor 2**
	Not asked	**Contractor 3**
	- Difficult to offer this as a general solution it requires a lot of effort to make it a functioning product that covers all aspects of toll that enables a lean and integrated TCI planning and management. --> Possible to develop a contractor specific or supplier specific solution to reduce the amount and variability of the data (e.g. focus only on a few products or only one contractor)	**Consultant 2**
	Not asked	**Consultant 3**
	Not asked	**Consultant 4**
	Not asked	**Consultant 5**
	Not asked	**Consultant 6**
	Not asked	**Consultant 7**
	Not asked	**Client 1**
	Not asked	**Contractor 4**

Appendix 6.4
Findings of the Evaluation Interviews per Category

Categorized Findings from Evaluation Interviews (Chapter 6)			
No.	**Findings**		**Interviewees**
	Main Findings		
	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 --> Less waste of time, money, recourses; more space on site, improved productivity and safety	11	**Client 1, TCI provider 1, Contractor 1, 3, 4, Consultant 2, 3, 4, 5, 6, 7**
	Contractor and TCI provider addressed the importance of integrating TCIs into the planning and management effort of a construction project as they significantly impact the time, costs and quality of a project and reduce waste --> Better planning and transparency benefits all parties involved in a project	5	**TCI provider 1, Contractor 1, 2, 3, 4**
	Automatic generation of TCI utilization 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**
	Approach of developing a data model for each construction project and use it for calculations and generating other 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, etc.)	2	**Consultant 5, 6**
	Benefits 1. Client: No direct benefit, but reliability of the contractors 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 stock and distribution, focus on complex structures, where automatic calculation is not applicable, proactive role with consultancy service in a project to address needs and requirements	12	**All**
	Obvious productivity increase 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**
	Solution offers a tool for the automatic planning of standardized formwork elements (given some assumptions), 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 simple in-situ wall structures --> Has to be further tested in a pilot project to reduce the amount of uncertainties and quantify the benefits	12	**All**
	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 of the solution	-	**-**
	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**
	Standardized ontologies must be established to describe the building data in its holistic context in order to ensure success of the solution	5	**Consultant 2, 3, 4, 5, 6**
	Centralized approach: Creating a solution-integrated and more advanced TCI engine which is able to calculate the precise	3	**Contractor 1, Consultant 3, 7**
	Decentralized approach: Outsource the calculation engines towards the different TCI provider who act as consultants for their specific product. TCI supplier receives the required project data and provides the demand of his products with the use of an advanced calculation engine as well as the service of planning and managing the items on the project	5	**TCI Provider 1, Consultant 2, 4, 5, 6**
	Easy accessible information for people who actually use the data in their work (dashboard for project manager and mobile application for the construction workers) and by that, solution reaches all relevant stakeholder	11	**Client 1, TCI Provider 1, Contractor 1, 2, 3, Consultant 2, 3, 4, 5, 6, 7**
	Integrate the created knowledge and transparency of the TCI utilization to site planning in order to optimize the site layout and logistics and enable a lean management	5	**Contractor 4, Consultant 2, 3, 4, 5**
	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 them is able to control the data flows and require certain specifications from the parties involved and therefore, easily implement such a solution	5	**Contractor 1, 3, 4, Consultant 4, 6**
	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 software solution	3	**Consultant 2, 4, 5**

0	**Current practice on construction projects**		
	From the perspective of consultants and one contractor, 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 --> Based on this estimation, the elements are ordered from the supplier (TCI overstock or shortage on site) --> Lack of TCI planning and monitoring on construction sites (No precise information which items are needed when and where)	5	**Contractor 4, Consultant 2, 3, 4, 5**
	In the perspective of most contractors, TCIs are considered in the site planning and management. However, there is no standard and automated way of doing this and it depends a lot on the contract, size and type of project in which level of detail they are planned and integrated into site management --> In small project or where no data is available, TCIs are only considered with a rough estimation --> For projects with a site model and structured building data, TCIs can be integrated in the site planning in order to optimize production workflow --> Only one contractor used an integrating solution that is able to automatically quantify TCI demands from the model data	3	**Contractor 1, 2, 3**
	General tendency of site planner to order much more TCIs than needed in a specific period in order to ensure a consistent construction flow and minimizing the risk of resource shortages --> Main driving force of the TCI quantification 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 --> During the project, the estimation is adjusted and either more items are ordered in short notice or items are returned	6	**TCI provider 1, Contractor 1, 4, Consultant 2, 3, 4**
	Missing transparency of which TCIs are needed when and where (no planning and monitoring) --> Items get lost or stolen	5	**Contractor 1, 4, Consultant 2, 3, 4**
1	**Benefits**		
A	General		
	Everyone in the production chain of a building project will benefit from an early planning of TCIs and a better collaboration and management of the construction site due to the gained transparency	1	**TCI provider 1**
	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 --> Less waste of time, money, resources; more space on site, **improved productivity and safety**	11	**Client 1, TCI provider 1, Contractor 1, 3, 4, Consultant 2, 3, 4, 5, 6, 7**
	Fascinating solution that tries to solve a real and complex problem in the construction industry with an open standard approach	3	**Consultant 2, 4, 5**
	Automatic generation of TCI utilization by using and integrating existing project data is targeting a niche in construction which is not yet fully optimized	5	**Consultant 3, 4, 5, 6, 7**
	Use of a very generic perspective (data modelling in construction projects with Linked Data) on a very narrow problem (formwork planning & management)	1	**Consultant 5**
	Early consideration of TCIs in project planning (Integration of TCI-Information and supplier expertise in the site & logistics planning) --> Planning the construction workflow in advance to improve decision making and a continuous and efficient production with a forward-looking and lean approach	4	**TCI Provider 1, Contractor 1, Consultant 4, 6**
	Approach of developing a data model for each construction project and use it for calculations and generating other 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, etc.)	2	**Consultant 5, 6**

B	Client		
	No direct benefit of the solution	12	**All**
	Reliability of the contractors offer (also less claims) as TCI-related parts are quantified with a thorough and transparent calculation, based on the tender material and not based on a untransparent and rough estimation	8	**TCI provider 1, Contractor 1, 3, 4, Consultant 2, 4, 5, 6**
	Better and updated project overview and more transparent construction site, reducing risk and uncertainty	9	**Client 1, TCI provider 1, Contractor 1, 3, Consultant 2, 3, 4, 5, 6**
	Due to better planning, higher chance of following the schedule without cost and time overruns	6	**TCI provider 1, Contractor 1, 3, Consultant 2, 3, 7**
	Generally higher awareness of safety on the construction site through integration of more aspects on the site planning and the generated detailed TCI information on a task level	2	**Consultant 6, 7**
	Due to less items and a better planning on site, the client might end up with a smaller construction site, which facilitates the process of project approval and reduces the costs and difficulties of setting up a construction site	1	**Consultant 7**
	If the client has high requirements and expectations on the construction site planning regarding productivity and safety, such a solution would guarantee a good site planning and provide a transparent and quantified proof of the site manager to comply with the clients requirements --> also for the client to meet safety regulations for construction sites (e.g. scaffolding requirements in dense urban cities) --> Client can also require an early consideration of the TCI planning and site logistics management in pre-design if such a solution would be on the market	2	**Consultant 4, 5**
C	Contractor		
	Automatic planning of TCIs adds great value in terms of **transparency** and **control** over the TCI utilization as all resources can be planned in advance and the construction **site layout and logistics** can be planned and managed accordingly (at least for simple structures in big in-situ concrete projects regarding formwork) --> Early Stage Assessment of TCIs (Contingency budget regarding TCIs and their management can be reduced a lot --> According to **Consultant 4**, there is a big discrepancy of the estimated contingency budget for TCIs and the actual number, TCIs contribute to the costs) --> According to **Contractor 4**, the main benefit would be the saving that are generated by the dynamic stock consideration with reduced items on site leading to less rent and less waste of valuable storage space	10	**TCI Provider 1, Contractor 1, 2, 3, 4, Consultant 2, 4, 5, 6, 7**
	Early stage assessment of TCI requirements --> The better and earlier TCI planning is integrated into a project, the better the site planning can benefit from the transparency regarding TCI utilization and save money and time on site	8	**Client 1, TCI provider 1, Contractor 1, 3, 4, Consultant 4, 5, 6, 7**
	Evaluate and compare TCI provider **bids** by running the solution with a default TCI set or with the actual product of the TCI provider, which he provides in the bid material	2	**TCI Provider 1, Contractor 1**
	Order precise amount of TCIs from the supplier in advance based on the calculated TCI utilization plan	4	**TCI Provider 1, Contractor 1, 2, 3, Consultant 7**
	Proactive consideration of TCIs for the contractor with **less reliability** on supplier and higher certainty that the items on site meet the TCI demands throughout the project --> Contractor can save a lot of money as he has the knowledge of what he needs and does not only rely on the estimation of the supplier	3	**TCI provider 1, Contractor 4, Consultant 7**
	Contractor can easily use the solution and, 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 are needed in the future. Information is always up-to-date as the system considers changes in the building model as well as the project schedule (e.g. from progress monitoring) --> **Site transparency**	5	**TCI Provider 1, Contractor 2, Consultant 2, 4, 5**
	Dynamic supply of TCIs to the construction site (just-in-time) and **lean site management** on site based on the transparent utilization plan reduces the amount of elements that are stored on site which is directly reducing the costs of rent of the planned items as well as the use storage space on site --> As most of the cost are based on the handling of the items on site (storage, logistics, installation, dismantling), the main cost benefit lies in the **reduction of resource hours**, spent to get the TCIs from the state of storage to the utilization and back.	7	**TCI Provider 1, Contractor 1, 2, 3, 4, Consultant 6, 7**
	Solution allows to **optimize** the whole **production flow** and to have a more efficient and **lean management** process of TCIs --> With more **control** and **transparency** of the construction site logistics, time and cost of rent and handling can be reduced a lot --> **Transparency** --> **Control** --> **Better Planning** --> **Lean Site Management** --> **Efficient Handling** --> **Time & Cost decrease**	8	**TCI Provider 1, Contractor 2, 3, 4, Consultant 2, 3, 5, 7**
	Better **site layout planning** and more efficient **space management** due to increased transparency and forward-looking site management approach --> citation form contractor at case study site: "Soon I'll be running out of space on the job site to put the formwork. Where shall I put the formwork?"	6	**TCI provider 1, Contractor 1, 2, 3, Consultant 6, 7**
	Solution is directly addressing the **needs of the workers** on site and deliver the generated value directly to the people who actually put the plan into practice (Site manager, construction worker), so construction tasks can be executed in a more efficient and secure manner, also integrating feedback from the construction site to what is planned	5	**Client 1, TCI Provider 1, Contractor 1, 3, 4**

D	TCI Provider		
	TCI provider benefits from a 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 and benefit from a close collaboration with the generated knowledge about the TCI utilization from the construction projects	5	**TCI Provider 1, Contractor 1, 3, Consultant 2, 3**
	Contrast: Depending on the business model, the created value of the solution might interfere with the interests of the TCI provider as they want to maximize the amount of items, they rent out to the construction site	4	**Contractor 4, Consultant 3, 6, 7**
	Get more involved in the project and provide a knowledge-based and collaborative service to the contractor	2	**Consultant 2, Consultant 5**
	Better and forward-looking planning of the own stock yard --> Less overstock due to transparent information how many elements are needed when on which project	4	**TCI Provider 1, Consultant 2, 6, 7**
	If the solution is applied for calculating the formwork demands for the simple structures, the supplier could put more time of design engineers into focusing on the complex and more important formwork constellations on the project	1	**TCI Provider 1**
	If the solution is used from the TCI-provider: Easy calculated offer for standard and simple building structures, automatically derived from the tender documents (building model) --> First mover benefit --> Can be directly integrated into the project, taking an active role, giving advice for the design and planning as well as calculate the TCI demands	5	**TCI Provider 1, Consultant 4, 5, 6, 7**
	As the TCI provider can give a detailed offer based on the building model, the offer is also not only evaluated by the cost per item, but rather by the cost impact on the whole construction project --> Supplier with higher item costs, but a much better workflow and system would end up winning the contract, as the project manager has the transparency to compare different offers on a much higher level of detail (over time and impact on site)	1	**Consultant 5**
	Higher per unit/cost but lower total prize in bid, as a project specific TCI utilization is offered which requires less TCIs --> More competitive prize	3	**Consultant 2, 3, 7**
E	Productivity		
	Obvious productivity increase 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**
F	Safety		
	Safety is generated generally as a secondary effect of a better and more transparent planning and management of TCIs	9	**TCI Provider 1, Contractor 1, 3, 4, Consultant 2, 4 , 5, 6, 7**
	If specific safety measures are applied: (1) all items in the formwork process have to be considered, (2) add direct safety means to the specific task to raise the awareness of and increase safety (e.g. Safety-Risk-Factor with notification, assembly instructions for site workers, checklists for each task which TCIs are there/installed and what is missing)	5	**TCI Provider 1, Contractor 4, Consultant 2, 3, 4**
2	**Validation and Further Development**		
A	General Validation		
	Solution offers a tool for the automatic planning of standardized formwork elements (given some assumptions), 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 simple in-situ wall structures	12	**All**
	Solution is only addressing the use case of formwork elements and therefore only benefits construction projects with large amount of in-situ walls --> Decision to create a specialized solution for a few TCI types and products or a platform solution that can generate utilization plans for multiple TCIs from multiple data sources with the option to outsource the calculation engine to the supplier	7	**TCI provider 1, Contractor 1, 4, Consultant 2, 3, 4, 5**
	Challenge of site implementation --> **Change management** and controlling means are needed to ensure that the involved parties update the data model as changes in project appear and that the construction workers also follow the plan --> All changes have to be included in the data model to update the TCI utilization plan --> Passive progress monitoring requires the construction workers to actively track their work and what items they used via a mobile application --> Construction workers are used to get a big box of material and then they look what fits and apply it (as playing with a box of LEGO). If everything is planned, the workers have to follow the plan and the plan has to be easily understandable and applicable for the workers	5	**TCI provider 1, Contractor 1, 2, 3, 4, Consultant 4**
	Next step of prototyping would be to **apply** the solution **to a construction site** where the process in-situ wall construction is analysed without the use of the proposed solution and with it. --> **Reduce the amount of uncertainties** in each step of the solution implementation and involve the interests of all involved people to further develop the solution --> Need to conduct case studies on projects to **quantify the benefit** of how much improved productivity and how much more safety is realized on site with the use of the proposed solution	7	**Client 1, TCI provider 1, Contractor 1, 2, 4, Consultant 3, 7**
	Prototype needs to 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	6	**Client 1, TCI Provider 1, Contractor 1, 2, 4, Consultant 7**
	Many stakeholder are restrictive in using integrated solution as they fear that it can automate the whole process and thus, is not aligned with their **interests** --> Some individual interests of stakeholder will be broken by interlinking the data and automatically deriving information	1	**Consultant 6**

B	General Further Development		
	Link the logistics status from supplier with the database, to know how many items are actually currently on site and when the next ones are delivered	2	**TCI Provider 1, Contractor 1**
	Active tracking with IoT-Sensors would further strengthen the solution and the control of the site manager as if elements on site get lost or are used for tasks they are not supposed to be used, the elements can be tracked and the plan can be adjusted --> Active tracking with IoT-sensors would allow to actively track the items on site without the need that construction workers have to actively monitor their work	2	**Consultant 2, 4**
	Solution must be further developed to also **integrate other TCI types** than formwork elements --> Calculation engine can be used to calculate **scaffolding** and **safety barriers** and by that highly increase the safety consideration on site (Also important from a client perspective to have safe sites and provide transparency about the safety considerations) --> For scaffolding and other TCIs, maybe more data is needed (load considerations) which has to be integrated as well --> Cranes, ladders, supports, etc.	5	**Contractor 3, 4, Consultant 2, 3, 4**
	Due to the challenge of site implementation, create a collaboration loop between the project manager and site workers who are able to update each other about changes from the planned data model or changes from the construction site --> Ability to **flexibly change the master plan** with the current circumstances on the construction site	4	**TCI Provider 1, Contractor 2, 3, Consultant 3**
C	Data Sources & Extraction		
	Using default TCI dataset is good in the beginning of a project to get a first estimation in order to get an overview of the space and logistics requirements on site and to compare bids of potential suppliers.	3	**Contractor 1, Consultant 4, 5,**
	Open standard solution that works with multiple BIM software applications or open BIM standards and is not dependent on specific software applications as Revit or VICO --> Using IFC-building models and integrating more scheduling tools --> Either have a solution that uses standardized data sources (model, schedule) and parses the data from source to RFD or make the software applications automatically extract the data as Linked Data (in RDF triplets) that the individual generators of the data can publish it directly to the Linked Data project environment	7	**TCI Provider 1, Contractor 1, Consultant 2, 3, 4, 5, 7**
	Building elements in the model have to be modelled as they are executed on site to ensure that the calculated TCI utilization plan represents exactly the processes on the construction site --> E.g. wall sequence is already known to also calculate wall endings and location system of LBS does not cut any walls and thus manipulate the TCI calculation output	3	**TCI Provider 1, Consultant 3, 4**
	Quantity extraction from a building model is risky as it requires a correct model setup --> BIM models are modelled differently and the solution should be able to flexibly handle variances in the BIM model --> Either put it clearly in the ICT agreement how the model must look like or create adjustment possibilities of the solution	2	**Contractor 2, Consultant 4**
	Need for a **data-driven project delivery** where a data model is created to support the construction project in every step --> **Structured data** in the construction projects with data model consideration and standardization how to describe and model the data --> Using data in construction is also quite new approach and the industry has to adapt to it, in order to fully implement such solutions (Feedback from the construction site directly to the data model)	6	**Contractor 2, 4, Consultant 2, 5, 6, 7**
	Standardized ontologies and language must be established to describe the building data in its holistic context --> Standardized ontology framework for the construction industry to describe e.g. the building elements, the schedule information and the TCIs which all stakeholder can use to provide their information in a standardized way --> Provide the suppliers with a standardized language (ontologies) to describe their products and share their data. Project manager can then use this data in combination with all other datasets from the project for a holistic data integration --> Integration of different stakeholder into a project is only possible with the standardization of data --> Difficult to classify such a complex context as the built environment and its project delivery	5	**Consultant 2, 3, 4, 5, 6**
	Data integrity is a very important aspect in such an integrated and data-driven process --> **QA-process** is needed to ensure that the input data complies with the specifications --> For full functionality of the solution, it requires more standardization and digitalization in the construction industry as false data extraction would result in chaos on site as the wrong TCIs are calculated and the benefits cannot be realized --> As construction project often lack of structured and holistic data, an effort is required to adjust and modify the data (building model and schedule) before it can be used for applying the solution --> Automated rule-based checking of the quality of the data sources (in LD via SHACL) to see if the individual data model complies with the requirements --> Could develop a dashboard to report the warnings back to the modeler, so the model gets modified accordingly to ensure the quality of the data sources and the security of the correctness of the output --> Supplier who would provide their service to the data model could have a pre validation of the model to check if all the required measures and geometries are existing to generate the TCIs demand	5	**Contractor 2, Consultant 3, 4, 5, 6**
	Quality assurance process and approval process is needed to make sure the data complies to the requirements and also the right version of the data is used for providing information for the TCI utilization plan --> Only what is approved can be used for this consideration --> Need to keep control over the process of what data is used and if the data has the required quality and how the data is processed to get information that benefits the process --> Very hard to implement a totally open and interlinked solution (risk of not getting the required data quality) as long as there is no 100% clean standard	3	**Consultant 3, 5, 6**
	Consideration of the technology level of the relevant stakeholder in the industry who would interact in a data environment with this solution --> Solution depends on the input of the different stakeholder in the construction chain and thus requires a certain level of technology of all the stakeholder --> Technology level of many stakeholder in the industry might not comply with the requirements --> Enable **manual input** to the solution and answer question how much of the process can be done without BIM	7	**Client 1, TCI Provider 1, Contractor 2, Consultant 2, 3, 6, 7**

D	Data Management		
	Right approach to use an open data format as Linked Data that can disrupt the industry and improve collaboration --> Linked Data allows to establish full data integration if all stakeholder collaborate with their specific input within the open project environment where the data model is hosted --> Pushes the data generation and distribution responsibility towards the supplier and then pulls the required data to create value for the project	2	**Consultant 2, 5**
	Good idea to use Linked Data and integrating it in a holistic and functioning approach to the existing process of project delivery	1	**Consultant 6**
	Data model has to be hosted by one party which provides access to specific data for the involved stakeholders	1	**Consultant 5**
	Implement it in the environments the stakeholder already use --> Integrate Byggeweb into the solution for example for data extraction and publishing as the ideal current scenario in the industry	1	**TCI Provider 1**
	Solution can also be done with usual data integration and the use of open APIs to extract the data and would probably be easier to apply the solution in the current industry than Linked Data --> Linked data is one approach to do it and a way of working that opens up the process to different stakeholder who could add their information to the project --> Linked Data is only one possibility to use such a solution and Triplets are only a way of specifying objects, its properties and describing their relationships and still requires a lot of effort to develop a holistic ontology framework for the industry	4	**Consultant 2, 3, 4, 5**
	Linked Data approach provides a framework to include IoT-data into the existing solution	1	**Consultant 5**
E	Data Processing & Querying		
	Create a more holistic solution that considers all aspects of planning and managing formwork elements (e.g. all items that are used, curing time for concrete, time of formwork in use, cycle plan with the work sequence to generate wall endings) --> Also include slabs, columns, beams in the formwork calculation engine	2	**TCI Provider 1, Contractor 4**
	Add historic information about the formwork elements, how many times the forms were already used and how many times can they still be reused before disposal	1	**TCI Provider 1**
	Make solution more usable for the user (e.g. Introduce some visual programming for building the rules for the calculation)	1	**Consultant 3**
	Challenge to automate the process of a holistic formwork calculation --> Use solution to calculate formwork elements for simple wall structures and enable a **manual input** from formwork experts for complex structures, but also for change management --> Fully automatic solution might not be able to cover all geometries and complexity of structures (If the solution solves 80% of the problem, but it takes 80% to solve the last 20% of the problem, then there is an issue for implementing the solution in real life) --> Filter options to only select the simple walls and mark the walls thar have to be calculated manually	8	**TCI Provider 1, Contractor 1, 2, 3, Consultant 3, 4, 5, 7**
	Option 1: Creating 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 (based on default TCI sets or real products) and derive a utilization plan (e.g. using advanced algorithms for a 2D-consideration of the formwork calculation) --> Solution must be able to calculate the correct demand of many different products! --> Contractor 4 also mentions that the catalogue of items will be quite big to create a holistic formwork calculation within one solution (including slabs, columns, beams in the formwork calculation engine and all other building elements for other TCI types)	4	**Contractor 1, 4, Consultant 3, 7**
	Option 2: Outsource the calculation engines towards the different stakeholder who act as consultants for their specific specialty --> TCI supplier receives the required project data and provides the demand of his products with the use of an advanced calculation engine as well as the service of planning and managing the items on the project --> Linked Data approach allows to share the required data to the stakeholders who provide their consultancy service --> e.g. A formwork design and utilization plan can be provided from PERI and the site manager can use this information for developing a lean site & logistics process that also gives feedback to and can optimize the project schedule --> Similar to an approach from TNO: BIIM BOTS - AUTONOMOUS CLOUD APPLICATIONS --> Create an open solution that can integrate as much bots as needed to the system architecture and establish an infrastructure for stakeholder integration so they would provide the project with the required input, based on their products --> No solution can do everything, so the more generic the data processing of the solution is, the better! (Focus on data integration and the holistic process flow to generate the desired benefits on site)	5	**TCI Provider 1, Consultant 2, 4, 5, 6**
	Create a holistic TCI planning and management tool that integrated all different types of TCIs	2	**Consultant 5, Contractor 4**

F	Data Visualizations & Distribution		
	Easy accessible information for people who actually use the data in their work (dashboard for project manager and mobile application for the construction workers) and by that, solution reaches all relevant stakeholder --> From the experience of **Contractor 3**, a dashboard on a big screen on the construction site works pretty well to provide a weekly overview in regular meetings (as in LPS) --> Also: mobile application for workers is already in use and can be used to inform/remind the worker directly on the TCI requirements for each task	11	**Client 1, TCI Provider 1, Contractor 1, 2, 3, Consultant 2, 3, 4, 5, 6, 7**
	Good to tailor-make the visualizations and data distribution to the stakeholder it is targeting --> PMs demand automated dashboards to control the construction site and receive updated information from the workers	3	**Contractor 1, 2, 4**
	As data is already there, individual dashboards can be developed for different stakeholders which different interests and focus areas	1	**Consultant 5**
	Great that the solution only works as a data model and doesn't draw elements into Revit as it is not needed and would only overcomplicate the 3D-model	1	**Consultant 5**
	Visualize the generated data in a plan or building model that shows the specific items. Further integrate the solution into a digital construction site planning (4D) that allows the worker to review the digital twin and also allows a safety professional to analyse the process digitally and thus, prevent accidents --> Modelling the TCIs and hand out shop-drawings for the construction workers (as IKEA instructions) would help the workers to get an overview of what is needed where and how to install it --> Auto-generated shop drawings	4	**Contractor 1, Consultant 5, 6, 7**
	Benefit of the solution has to be made visual clearly understandable to be implemented in the conservative industry. --> Comparison between how much time they spend on a conventional project for handling formwork and how much they could save with the proposed solution (in terms of time, resources and money)	2	**TCI Provider 1, Contractor 2**
	Add assembly instructions for each task in the mobile app in order to raise the awareness for safety and allow the construction workers to follow the instructions for a safe installation and dismantling of the TCIs for each task	2	**TCI Provider 1, Contractor 4**
	In the mobile application, add that the workers receive a checklist of what task are planned today and the next day including TCI quantities and where the TCIs are currently supposed to be located	1	**Contractor 1**
	Use the dashboard on a screen in a construction container on site to provide a good overview of the TCI utilization for the construction teams and the foremen to plan the upcoming days --> Limit the data to what is actually needed from the foreman (Gantt diagram with task information, location information and TCI quantities per task)	2	**Contractor 1, 4**
	Safety Risk Factor can be highlighted in each task in green, yellow and red, identifying the risk level of the task regarding the utilization of the TCIs	1	**Contractor 4**
	Further development could be to include an XML output for directly communicating with an ordering system of a supplier --> Click on app to automatically request TCIs	1	**Consultant 3**
	Use augmented reality to compare what is planned to what is installed --> E.g. AR at PERI or Pascal --> Combination of AR and the automated planning of the presented solution could be very interesting --> According to **Contractor 4**, image recognition could also check if what is planned is actually executed on site	2	**Contractor 4, Consultant 7**
G	Active Tracking with IoT-Sensors		
	Active TCI tracking should be the next step to even more increase the transparency and control over the TCI management with real time data from the construction site --> Quite easy implementation as the solution is cheap, easy to use and cloud based --> Not only knowledge where the forms are supposed to be, but where they are actually located --> Would provide the construction project with automatic feedback and control over the workflow with real-time information of what is where to compare planned vs. reality --> Would also allow to better integrate the solution to the site planning and management (Real time site logistics with location consideration by using IoT-sensors) --> Active tracking would reduce the responsibility of the workers to track their work manually --> Less risk of human failure --> Would definitely improve the reliability and functionality of the solution especially with items that are reused on site multiple times as formwork (e.g. If a dynamic stock with just-in time delivery is chosen and then the workers cannot find the items and there are not enough spare items on site, you are really doomed) --> Active tracking would reduce the risk of workers not following the plan	7	**Contractor 1, 3, Consultant 2, 3, 4, 5, 6**
	- Instead of IoT-sensors, which send location information of the items to the database, the TCIs can be equipped with QR codes, which a foreman can scan --> Information of where the scanned item is will be directly communicated with e.g. the crane who then knows where to get the item from and where to move it next --> Transparent information due to active TCI tracking through workers reporting their activities --> Would create knowledge where the items are, where they have to be moved, when they are installed and when they ae ready for dismantling --> Requires an active role of the construction worker, tracking the construction workflow --> change management --> However, is seen more efficient and better than using location-based IoT-sensors, as the workers can add much more information in their reporting than only the location (e.g. issues, delay, damage, etc.)	1	**Contractor 4**
	Workers should also get insights and benefit from the active tracking, e.g. if a item is not where it is supposed to be, the worker can locate an item of the same type which is located nearby	1	**Consultant 6**
	Recognizing items and their location with image recognition might be better as the technology is emerging super fast --> Recognize the size and type of the items on site --> how many items are used/ on site	2	**Contractor 4, Consultant 3**
	Sensors (if integrated robustly in the elements) can also have much more benefits as they would count the use of a form and how many times it can still be reused before disposal	1	**Contractor 1**
	Difficult to install a sensor that withstands this, high risk of breaking the sensors during construction --> Would be too much of an effort and not beneficial for a formwork supplier to apply IoT-Sensors to all items (for some preassembled parts, it is already implemented) --> Sensors would need to be on every item to ensure usability of the tracking system. Not feasible right now and no company currently does that	1	**TCI Provider 1**
	Workers might not want to be tracked? --> Need to see the benefit in a more transparent and better workflow to actually utilize the solution	1	**Consultant 6**

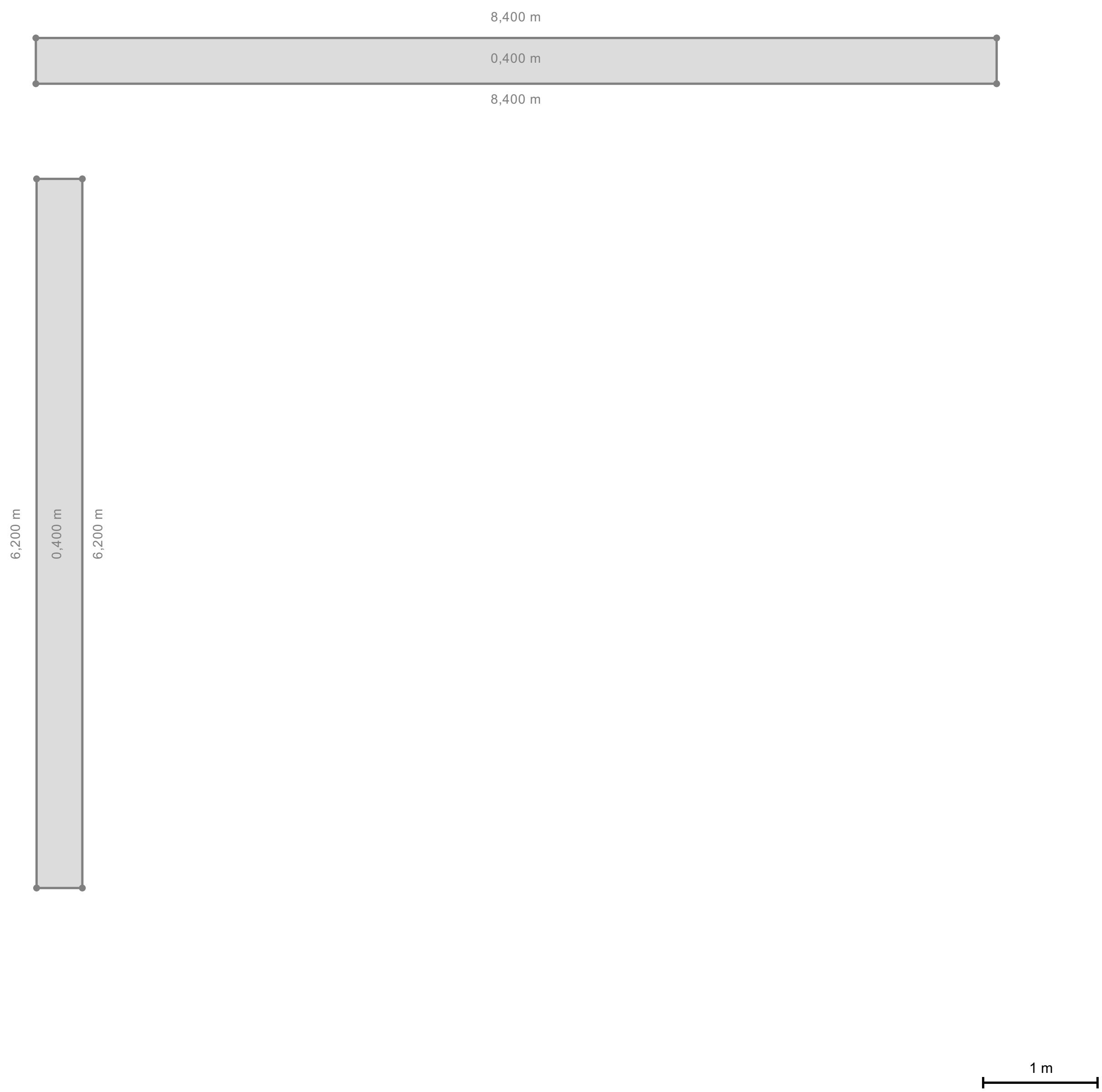
H	Scalability of solution for other TCIs		
	Open system of the solution can be applied and scaled to many different TCIs which have a relation with what is modelled and therefore can be quantified by a rule-based calculation engine --> Generic and data-driven approach of linking TCIs to existing BIM data can be applied to several areas --> General problem of all TCIs is the lack of information regarding their utilization	11	**Client 1, TCI Provider 1, Contractor 1, 2, 4, Consultant 2, 3, 4, 5, 6, 7**
	Each TCI type requires an individual ruleset to calculate its demand for the project --> Where to get the data from, what parameters are required, etc. --> Furthermore, a system has to be established that applies a tailor-made calculation method to the different products within each TCI type group.	2	**Consultant 3, 5**
	Calculation engine can be used to calculate **scaffolding** and **safety barriers** and by that highly increase the safety consideration on site (Also important from a client perspective to have safe sites and provide transparency about the safety considerations) --> For scaffolding and other TCIs, maybe more data is needed (load considerations) which has to be integrated as well	5	**Contractor 3, Consultant 2, 3, 4, 6**
	Solution can also be applied to precast industry for planning and calculating the demand of PushPullProps (supporting the precast elements until they are self-sustaining) --> Big market in Denmark for precast concrete and need to plan the TCIs in this industry!	2	**TCI Provider 1, Consultant 6**
	Option 2 of the suggested further development consists of a generic platform solution with a Linked Data environment to which all kind of service provider in the construction project could integrate the demand of their products for the given project specifications	2	**Consultant 4, 5**
	Machines (e.g. cranes) and other TCIs which cannot directly be linked to the building model are more related to where it is located and how far it can reach --> Can be integrated in the next step of site logistics planning	1	**Consultant 6**
	Get feedback from construction workers about which TCIs should be implemented in the solution --> Depends which items cause the most difficulties and where the workers are convinced that the solution will add value	3	**Contractor 1, 2, 3**
I	Integration to Site Planning & Management		
	Integrate the created knowledge and transparency of the TCI utilization to site planning in order to optimize the site layout and logistics and enable a lean management --> Solution is only providing the raw data of how much is needed where, but doesn't suggest, for example, where it has to be stored before and after use --> Digital integration into a site & logistics optimization tool --> Generating a data driven site & logistics plan for the construction site which takes into account different aspects as the quantities, location, geometry, logistics and space requirements of TCIs, PCIs as well as the construction workers	5	**Contractor 4, Consultant 2, 3, 4, 5**
	Active tracking of the TCIs via IoT-sensors would further foster the integration of the solution to the site management --> Where do you store it and check how does it move --> Controlling unit for active site monitoring to check compliance with the plan --> This can be done with location-sending sensors, QR-codes or also a camera which is identifying the TCI types and location on site	3	**Contractor 4, Consultant 3, 5**
	Location based integration of construction elements is the key for enabling a more efficient site management	5	**Contractor 1, 3, 4, Consultant 3, 4**
	Write back TCI utilization data to schedule and model and try out different scenarios of the model or schedule (e.g. with AI) for improving the project delivery (e.g. avoid special formwork elements, reduce amount of formwork sizes, adjust schedule according to TCI information (requirements, availability, etc.)) --> Optimization of model, schedule and site logistics based on the calculated TCI information --> Full integration in the construction process (Where is the stock, how are the items moved from one part of the construction site to another part, which items are used/ available right now, where to store the items after use to ease the distribution to the next installation location)	3	**Consultant 2, 4, 5**
	Consider a packaging service from the TCI supplier or Site manager --> With the information of what items are required where on site, a responsible party could set up and locate all the items which are needed for each construction activity on the location, where they are needed --> Would allow a lean management with an efficient space utilization and construction flow on site and reduced waste in terms of material, time and space	1	**Consultant 4**

3	**Business Model**		
A	Integration in Existing Project Delivery (current industry)		
	Linked Data approach in solution requires a lot of effort in terms of standardization, QA of the used project data and a general increase of the level of technology and an open mindset regarding new technologies of all stakeholder in the industry --> Limitations in the current industry have to be considered in the solution and thus, some modifications are required to implement it in the current industry	1	**Contractor 1**
	General contractor with a Design&Build contract could implement the solution by setting up a 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 --> As they have the whole value chain under them, they are able to control the data flows and easily implement such a solution --> Contractor benefits the most of implementing the solution as it will give him control and transparency over the site layout and workflows --> If contractor is not involved from the beginning, it is difficult to demand a certain data integrity and thus, the solution is difficult to be realized --> **Client** cannot drive the use of such a solution as they do not have enough impact on the value chain (could require such a solution and then shift the responsibility for implementation towards the contractor or a consultancy) --> **TCI provider** do not have a contractual relationship with the data provider and therefore would rely on something they cannot guarantee	5	**Contractor 1, 3, 4, Consultant 4, 6**
	For the implementation of the solution for a **contractor**, a consultant could be involved 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 --> Small contractors would use the solution as a consultancy service	5	**TCI Provider 1, Contractor 1, 4, Consultant 2, 4**
	Providing a software is not sufficient as there is always a need to accompany the software with a consultancy service (at least in the beginning)	3	**TCI Provider 1, Consultant 2, 3**
	Could be an **additional service** of the site & logistics management with a data-driven approach to optimize the site logistics management either, offered by an external company as Ajos etc. or directly from the contractor	2	**Consultant 2, 6**
	A modified solution approach with usual data integration and the use of **open APIs** to extract the data will be implemented easier in the current settings of the industry --> Would still require a standardization of the APIs, but this approach is more likely to be realized in contrast to Linked Data	3	**Consultant 2, 3, 4**
	System architecture of the proposed solution with data extraction from the different authoring tools in a project is needed now, as the Linked Data approach is not yet implemented in the industry	1	**Consultant 5**
	Consultancy as a service can be offered by the specialized TCI provider who are consulting the contractor with the utilization of their specific product --> Need to gain access to the data model from the general contractor or a client consultancy --> Would provide a competitive advantage for the TCI provider	1	**Consultant 6**
	Consultancy service is required, that sets up the linked data platform for each project and either develops the calculation engines for the TCIs in the project or helps the TCI provider to develop their own calculation engine to share their data with the project platform.	1	**Consultant 4**
	Be aware of the impact of the solution to the different stakeholder and their specific interests --> Might require new roles or make existing roles obsolete	2	**Consultant 6, 7**
B	New Project Delivery System (Linked Data vision) --> See option 2 in category 2E		
	Linked Data project delivery vision where all stakeholders generate and own their data, but provide it 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 software solution --> Different stakeholder would provide their information as consultancy-as-a-service for a specific part of the project	3	**Consultant 2, 4, 5**
	New roles and responsibilities will arise in the market and we need to go in this direction of getting better data --> Role of generating the project data model, hosting it centrally, providing access to specific data and integrating new data to the model will gain more and more importance	4	**Contractor 2, Consultant 2, 5, 6**
	One party is centrally hosting the data model from the beginning of the project and providing and integrating data from the different parties involved in the project as the project evolves --> Question of who will be responsible for hosting the data needs to be decided project specifically --> In the construction phase, the responsibility could go to the general contractor	2	**Consultant 4, 5**
	Make the BIM authoring tools automatically extract the data as Linked Data (in RDF triplets) to directly communicate with the data store of the data model --> individual generators of the data can publish it directly to the Linked Data project environment	1	**Consultant 5**
	In the construction phase, the contractor is gaining most access to the model in order to plan the site and logistics and have more control over construction flow	2	**Consultant 4, 5**
	Supplier and sub-contractor gain access to the specific data, they need to calculate the demand of their product/ service and integrate it to the data model and the existing site workflow --> Will act as a service provider for the project and includes his expertise and input to optimize the model, schedule and site management regarding costs of TCIs (especially handling) and the production flow on site	3	**Consultant 4, 5, 6**
	Scenario is realistic as the all the data is there and also smaller companies will be able to publish their project input or at least provide the raw data for the engineer to translate it into the Linked Data format --> Industry is aiming towards this scenario --> Requires a change in the mindset of the people to work in an open project environment --> Requires a standardization process in the whole industry to develop the required ontologies	5	**Contractor 3, Consultant 2, 4, 5, 6**

Appendix 7.1

PERI-Quicksolve_SingleWall

Plan



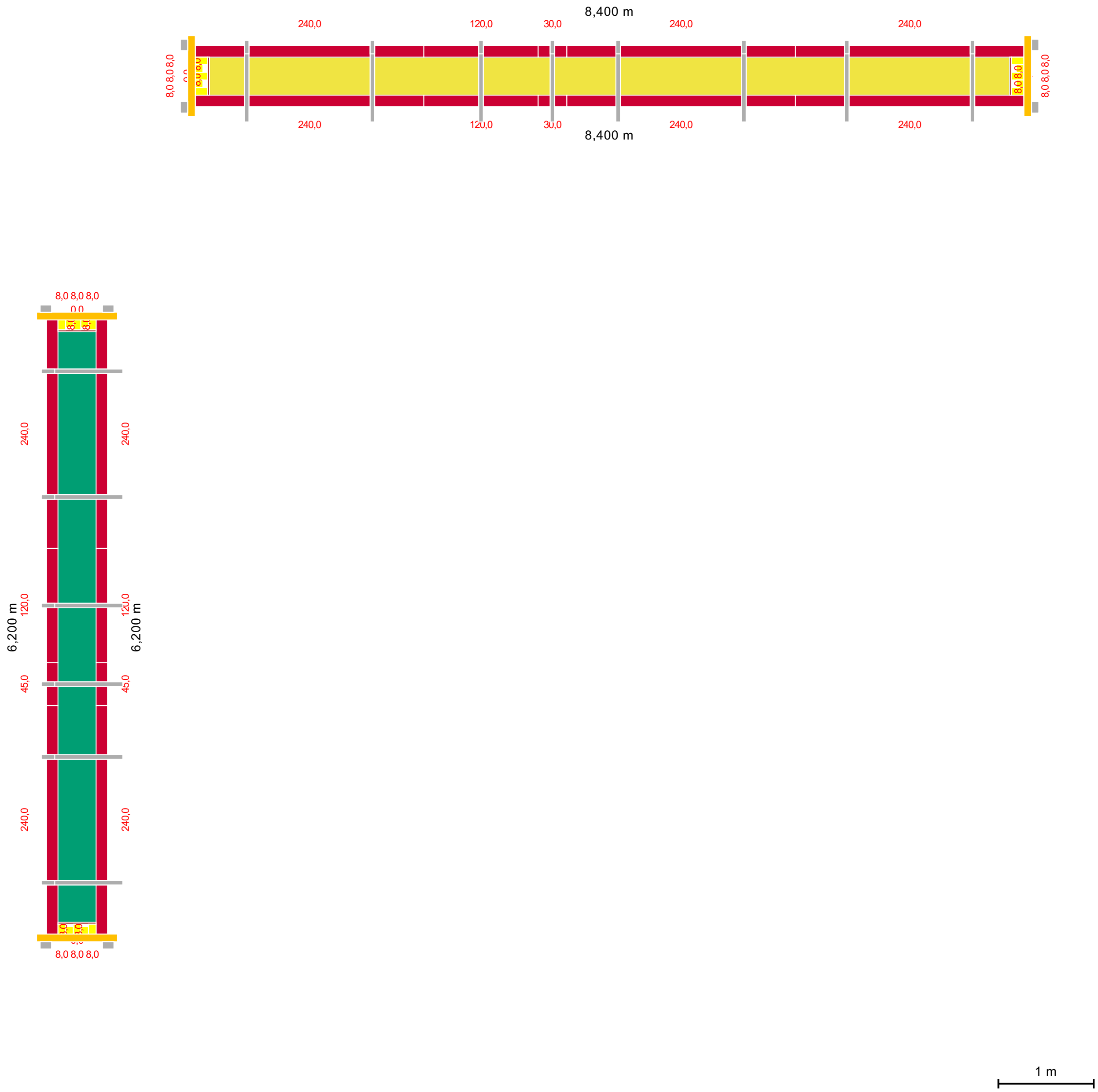
Disclaimer

- There are no binding instructions acc. to the general arrangement from PERI in this offer drawing. The offer drawing is not sufficient for the use on-site; Therefore a general arrangement drawing is required.
- This formwork suggestion does not replace the use of Assembly Instructions, in terms of the necessary safety measures.
- Stopend formworks, working scaffoldings and bracings are possibly not part of the offer and have to be supplied by client.
- The standard section illustrates a possible variant for safe use of the system shown.
- This PERI formwork is designed for a maximum number concrete pressure of 60 kN/m².

The corresponding assembly instruction must be observed!

	TCI-Demo_SingleWall	
PERI GmbH	Denmark	4/9/2020
89264 Weißenhorn		
Tel. +49 (0)7309.950-0	MAXIMO270	

Cycles



■ Cycle 1
■ Cycle 2

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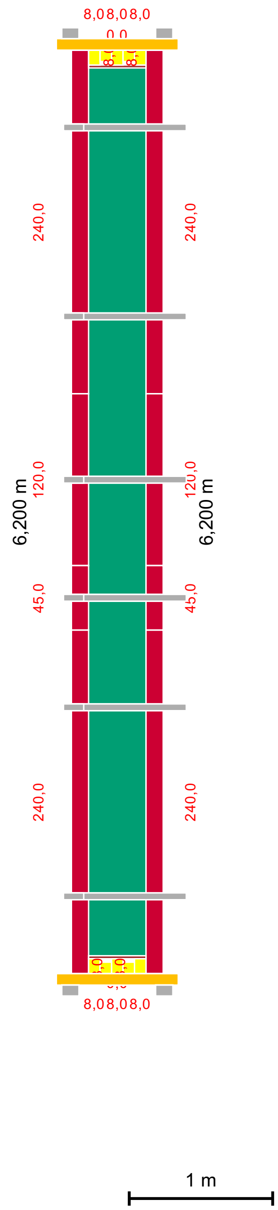
MAXIMO270

Cycle 1



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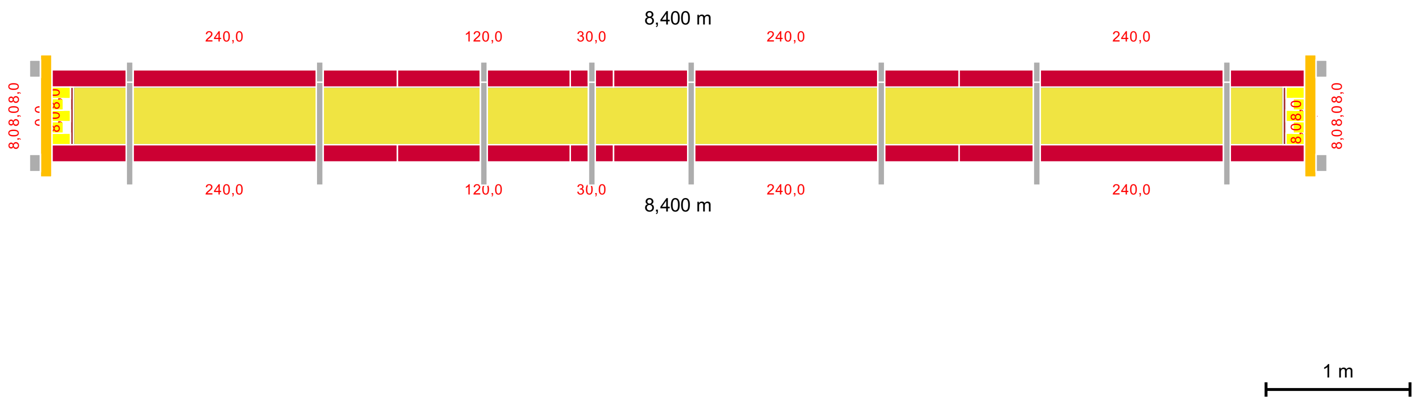
Tel. +49 (0)7309.950-0	MAXIMO270	

Cycle 2



Disclaimer

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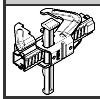
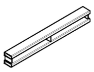
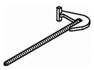
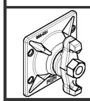
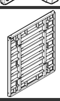
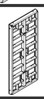
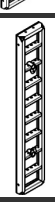
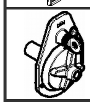
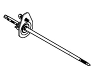
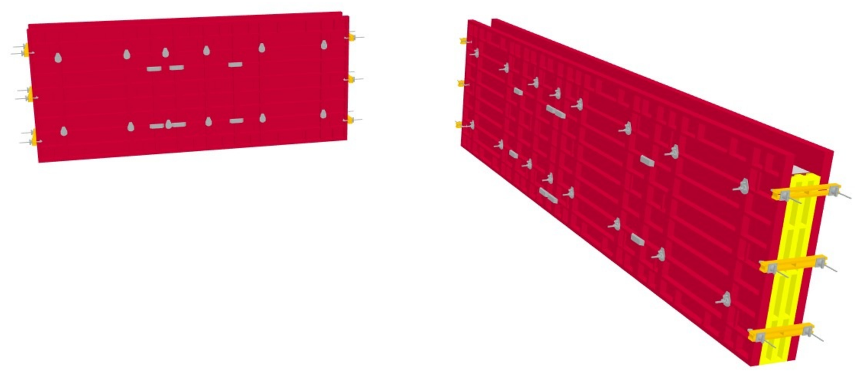
The corresponding assembly instruction must be observed!

	TCI-Demo_SingleWall	
PERI GmbH	Denmark	4/9/2020
89264 Weißenhorn		
Tel. +49 (0)7309.950-0	MAXIMO270	

Parts list

		1	2	Maximum Pcs.	Correction Pcs.	Sum Pcs.	Weight kg
	ALIGNMENT COUPLER BFD Art.-No. 023500 4.58 kg	12	16	16	0	16	73.28 kg
	WALER 85 Art.-No. 023551 8.52 kg	6	6	6	0	6	51.12 kg
	TRIO BULKHEAD TIE TS, GALV. Art.-No. 023640 1.14 kg	12	12	12	0	12	13.68 kg
	WINGNUT PIVOT PLATE DW15 GALV Art.-No. 030370 1.66 kg	12	12	12	0	12	19.92 kg
	MAXIMO-PANEL MX 270X240 -/- Art.-No. 112006 336.00 kg	4	6	6	0	6	2016.00 kg
	MAXIMO-PANEL MX 270X120 Art.-No. 112022 186.00 kg	2	2	2	0	2	372.00 kg
	MAXIMO-PANEL MX 270X 45 Art.-No. 112078 77.50 kg	2	-	2	0	2	155.00 kg
	WINGNUT MX15 Art.-No. 112386 2.58 kg	12	16	16	0	16	41.28 kg
	TIE MX15 30-40 Art.-No. 112464 4.43 kg	12	16	16	0	16	70.88 kg
	MAXIMO-PANEL MX 270X 30 Art.-No. 112090 61.80 kg	-	2	2	0	2	123.60 kg
	Plywood Width: 40,0 cm, Height: 240,0 cm, Depth: 2,1 cm	2	2	2	0	2	
	Filler timber Width: 8,0 cm, Height: 240,0 cm, Depth: 10,4 cm	6	-	6	0	6	
	Filler timber Width: 8,0 cm, Height: 8,0 cm, Depth: 4,0 cm	20	20	20	0	20	
	Filler timber Width: 8,0 cm, Height: 240,0 cm, Depth: 12,9 cm	-	6	6	0	6	
							2936.76 kg

Screenshot 1



Disclaimer

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- Stopend formworks, working scaffoldings and bracings are possibly not part of the offer and have to be supplied by client.
- The standard section illustrates a possible variant for safe use of the system shown.
- This PERI formwork is designed for a maximum number concrete pressure of 60 kN/m².

The corresponding assembly instruction must be observed!

PERI	**TCI-Demo_SingleWall**	
PERI GmbH	Denmark	4/9/2020
89264 Weißenhorn		
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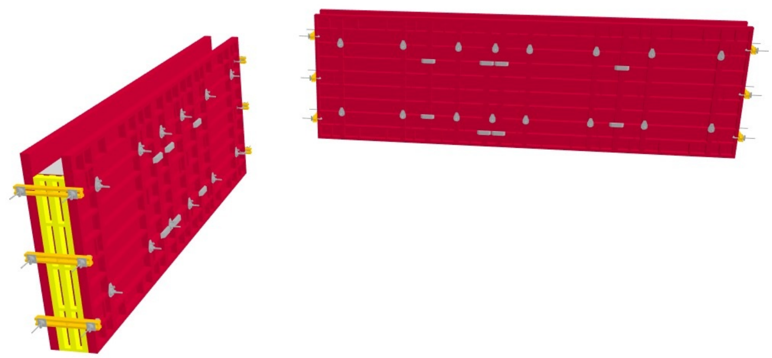
Screenshot 2



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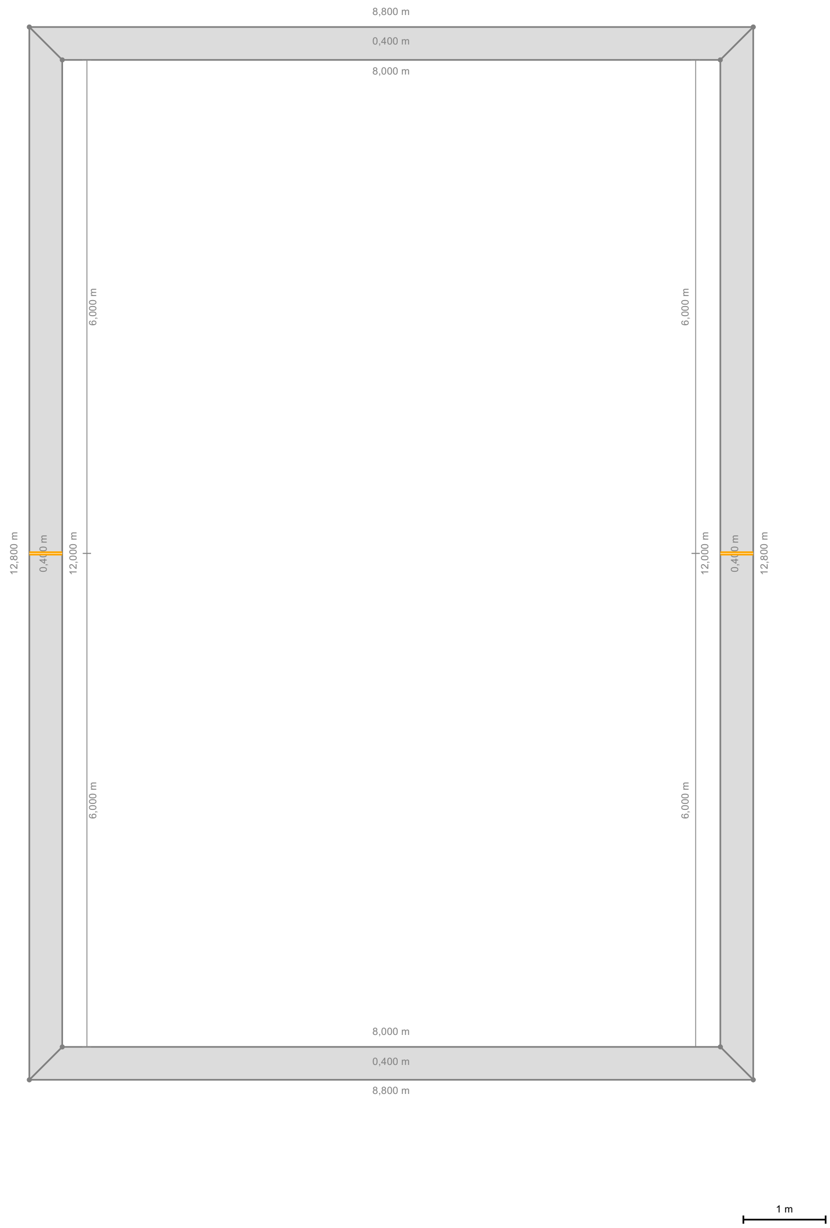
PERI GmbH	Denmark	4/9/2020
89264 Weißenhorn		
Tel. +49 (0)7309.950-0	MAXIMO270	

Appendix 7.2

PERI-Quicksolve_DemoGF

Plan



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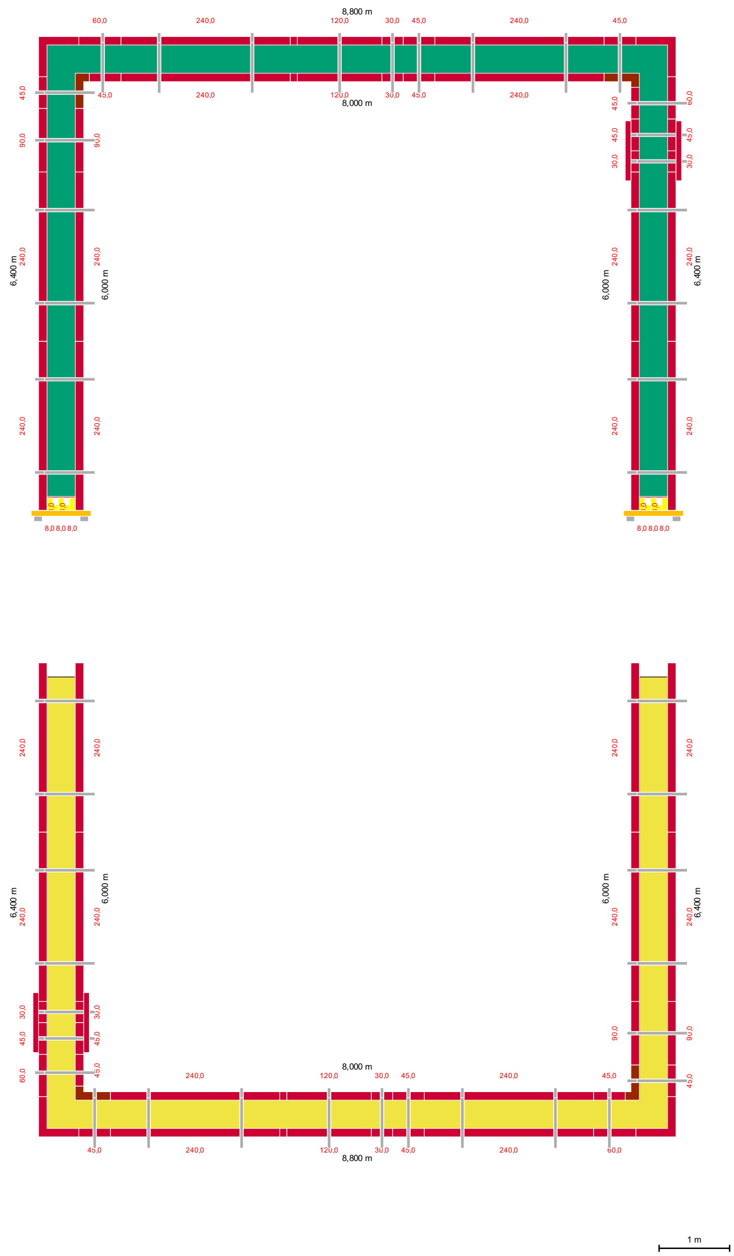
The corresponding assembly instruction must be observed!

	TCI-Demo-test2	
PERI GmbH	Denmark	3/31/2020
89264 Weißenhorn		
Tel. +49 (0)7309.950-0	MAXIMO270	

Cycles



- Cycle 1
- Cycle 2

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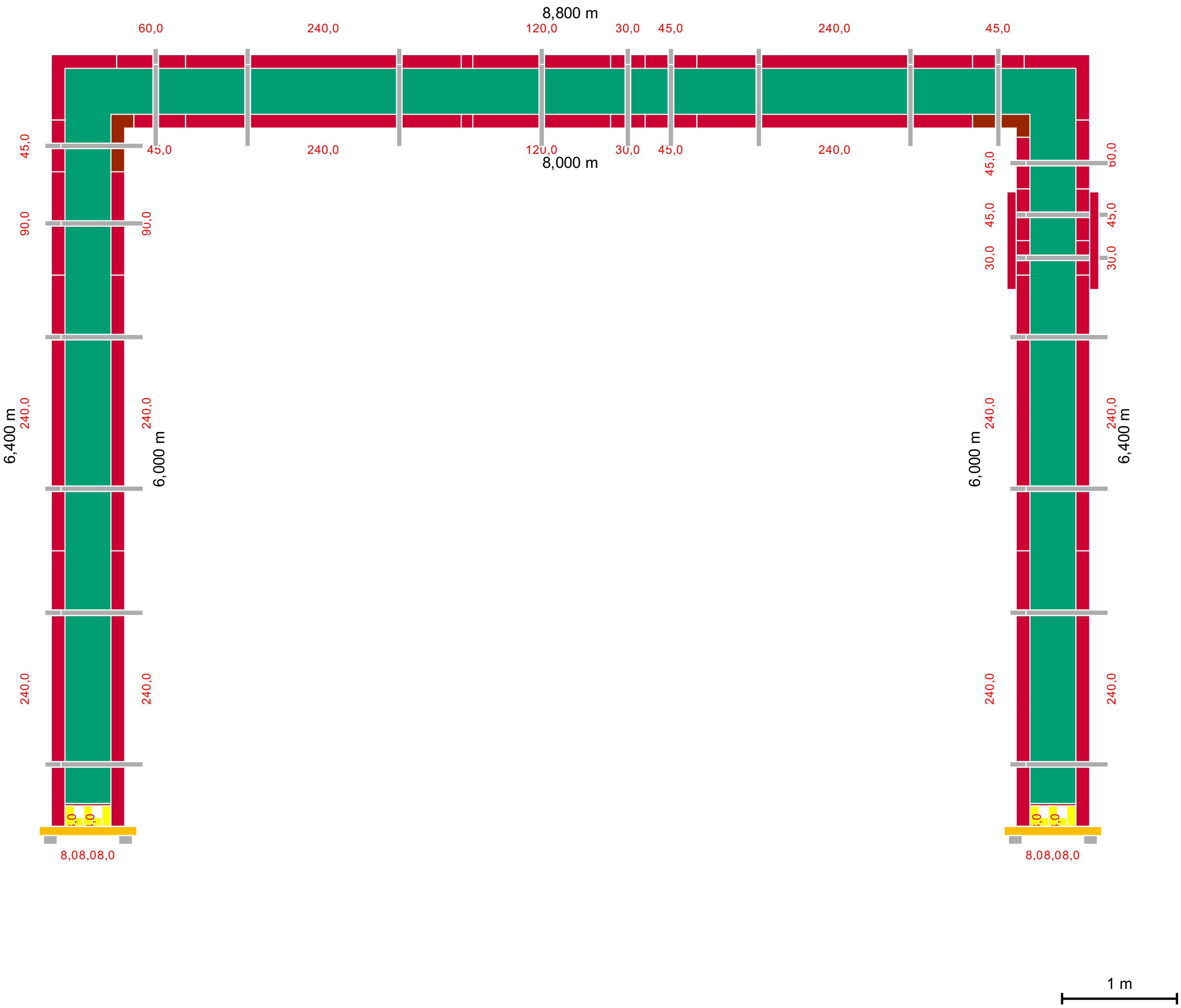
The corresponding assembly instruction must be observed!

	TCI-Demo-test2	
PERI GmbH	Denmark	3/31/2020
89264 Weißenhorn		
Tel. +49 (0)7309.950-0	MAXIMO270	

Cycle 1



Disclaimer

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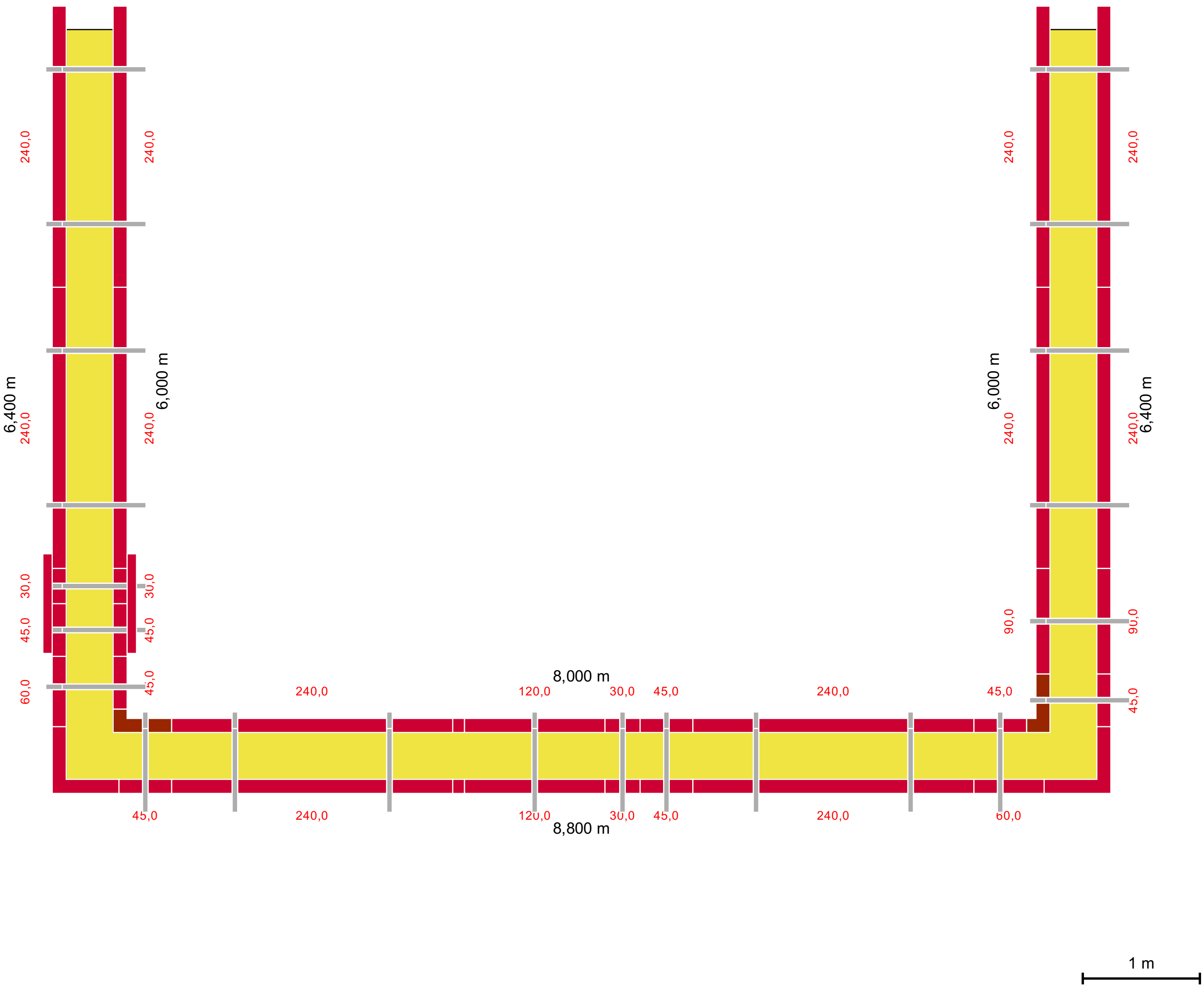
- This PERI formwork is designed for a maximum number concrete pressure of 60 kN/m².

The corresponding assembly instruction must be observed!

	TCI-Demo-test2	
PERI GmbH	Denmark	3/31/2020
89264 Weißenhorn		
Tel. +49 (0)7309.950-0	MAXIMO270	

Cycle 2



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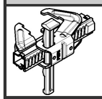
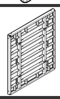
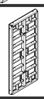
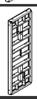
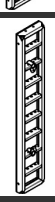
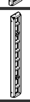
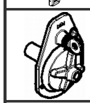
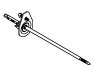
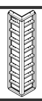
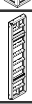
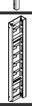
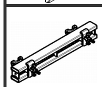
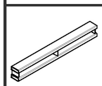
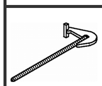
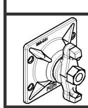
The corresponding assembly instruction must be observed!

	TCI-Demo-test2	
PERI GmbH	Denmark	3/31/2020
89264 Weißenhorn		
Tel. +49 (0)7309.950-0	MAXIMO270	

Parts list

		1	2	Maximum Pcs.	Correction Pcs.	Sum Pcs.	Weight kg
	ALIGNMENT COUPLER BFD Art.-No. 023500 4.58 kg	81	81	81	0	81	370.98 kg
	MAXIMO-PANEL MX 270X240 -/- Art.-No. 112006 336.00 kg	12	12	12	0	12	4032.00 kg
	MAXIMO-PANEL MX 270X120 Art.-No. 112022 186.00 kg	2	2	2	0	2	372.00 kg
	MAXIMO-PANEL MX 270X 90 Art.-No. 112045 134.00 kg	2	2	2	0	2	268.00 kg
	MAXIMO-PANEL MX 270X 45 Art.-No. 112078 77.50 kg	8	8	8	0	8	620.00 kg
	MAXIMO-PANEL MX 270X 30 Art.-No. 112090 61.80 kg	4	4	4	0	4	247.20 kg
	WINGNUT MX15 Art.-No. 112386 2.58 kg	44	44	44	0	44	113.52 kg
	TIE MX15 30-40 Art.-No. 112464 4.43 kg	44	44	44	0	44	194.92 kg
	OUTSIDE CORNER MXA 270 X 45 Art.-No. 112806 157.00 kg	2	2	2	0	2	314.00 kg
	MULTI PANEL MXM 270X60 Art.-No. 112849 108.00 kg	2	2	2	0	2	216.00 kg
	WALL THICK.COMP. MX 270X10 ALU Art.-No. 114128 10.00 kg	2	2	2	0	2	20.00 kg
	INSIDE CORNER MXI 270 X 50X20 Art.-No. 115255 103.00 kg	2	2	2	0	2	206.00 kg
	COMPENSATION WALER MAR 85/3 Art.-No. 124941 14.10 kg	2	2	2	0	2	28.20 kg
	WALER 85 Art.-No. 023551 8.52 kg	6	-	6	0	6	51.12 kg
	TRIO BULKHEAD TIE TS, GALV. Art.-No. 023640 1.14 kg	12	-	12	0	12	13.68 kg
	WINGNUT PIVOT PLATE DW15 GALV Art.-No. 030370 1.66 kg	12	-	12	0	12	19.92 kg
	Plywood Width: 40,0 cm, Height: 240,0 cm, Depth: 2,1 cm	2	-	2	0	2	

Parts list

		1	2	Maximum Pcs.	Correction Pcs.	Sum Pcs.	Weight kg
	Filler timber Width: 8,0 cm, Height: 240,0 cm, Depth: 17,9 cm	6	-	6	0	6	
	Filler timber Width: 8,0 cm, Height: 8,0 cm, Depth: 4,0 cm	20	-	20	0	20	
							7087.54 kg

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.