THESIS FOR THE DEGREE OF DOCTOR OF TECHNOLOGY

Collaborative production planning with BIM

Design, development and evaluation of a Virtual Production Planning system

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Department of Architecture and Civil Engineering
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Abstract

Construction projects have for a long time been characterized by increased specialization, low productivity, and a fragmented information exchange culture, resulting in inefficient work processes, with time delays and budget overruns. Research within the context of construction planning and scheduling and IT points to improving communication, collaboration, and cooperation to address these problems. However, the focus has been chiefly on production planning processes and scheduling tools and software. Research also points to collaborative user-friendly scheduling systems remaining under-researched; even though collaborative approaches have been introduced, the technological support and implementations are lacking. In this context, this thesis presents a novel collaborative planning and scheduling process and software system, supporting multiple modes of interaction such as individual review, planning, collaborative scheduling and review work in 4D, both co-located and remote. A Design Science Research approach was used to identify requirements that guided the collaborative production planning system's design and development and evaluations. These evaluations show that implementing the collaborative planning and scheduling system enhances understanding of the planning and scheduling of projects and supports both individual and group work. The developed system facilitates information gathering when creating activities and improves collaborative production of the schedule. Furthermore, the new collaborative setting shortens the length of planning workshops while simultaneously increasing the quality output. Thus, the thesis contributes to the body of knowledge of collaborative production planning, collaborative IT systems in construction, how these systems can support communication and collaborative processes in a social context, and how a design science approach could be used in this setting.

Keywords: Collaborative Production Planning, Scheduling, Construction Informatics, BIM, Construction IT

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Mikael Viklund Tallgren

Appended papers

Paper I:

An empowered collaborative planning method in a Swedish construction company - A case study.

Viklund Tallgren, Mikael; Roupé, Mattias; Johansson, Mikael, in *Proceedings of the 31st Annual Association of Researchers in Construction Management Conference (ARCOM)*, 2015, Lincoln, United Kingdom, 7-9 September 2015, p. 793-802

Paper II:

BIM-tool development enhancing collaborative scheduling for pre-construction.

Viklund Tallgren, Mikael; Roupé, Mattias; Johansson, Mikael and Bosch-Sijtsema, Petra, in *International Journal of Information Technology in Construction*, Volume 25, Pages 374-397, 2020

Paper III:

4D modelling using virtual collaborative planning and scheduling.

Viklund Tallgren, Mikael; Roupé, Mattias; Johansson, Mikael, Submitted to *International Journal of Information Technology in Construction*, April 2021, revised paper submitted September 2021, Accepted for publication October 2021, in production.

Paper IV:

A BIM-based collaborative production planning system: Design, development, and evaluation.

Viklund Tallgren, Mikael; Roupé, Mattias; Johansson, Mikael, Submitted to *Journal of Construction Engineering and Management*, October 2021

Distribution of work

Paper I: ***An empowered collaborative planning method in a Swedish construction company - A case study.***

Mikael Viklund Tallgren presented the work at the 31st Annual Association of Researchers in Construction Management Conference. The study was conducted in concert with the other authors. The ideas and results were analysed and discussed together, with Mikael V.T. as the primary author.

Paper II: ***BIM-tool development enhancing collaborative scheduling for pre-construction.***

The study behind the paper was conducted in collaboration; ideas were analysed and discussed between the authors. Mikael V.T. was the primary author with Mattias R., Mikael J. and Petra Bosch-Sijtsema contributing to the background, analysis and discussion. MIkael VT did the final writeup.

Paper III: ***4D modelling using virtual collaborative planning and scheduling.***

The paper is an extensive extension of a conference paper, as an invited paper to the special issue for the CONVR conference in The Journal of Information Technology in Construction. The paper connects this thesis's main project with three related research projects, with Mikael V.T. as the primary researcher of the main project. The other two projects were on VR in the design phase, and VR at the construction site was conducted primarily with Mattias R. and Mikael J. The compilation was conducted in collaboration between the authors; ideas and results were analysed and discussed together. Mikael V.T. was the primary author and finalised the paper.

Paper IV: ***A BIM-based collaborative production planning system: Design, development, and evaluation.***

The paper connects this thesis's main project with three related research projects, with Mikael V.T. as the primary researcher of the main project. The other two projects were on VR in the design phase, and VR at the construction site was conducted primarily with Mattias R. and Mikael J. The compilation was conducted in collaboration between the authors; ideas and results were analysed and discussed together. Mikael V.T. was the primary author and finalised the paper.

Additional publications

Journals

”Virtual Collaborative Design Environment: Supporting Seamless Integration of Multitouch Table and Immersive VR”
Roupé, Mattias; Johansson, Mikael; Maftei, Laura; Lundstedt, Rikard Viklund Tallgren, Mikael. In *Journal of Construction Engineering and Management*, 146(12): 04020132. DOI: 10.1061/(ASCE)CO.1943-7862.0001935.

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Roupé, Mattias; Viklund Tallgren, Mikael; Johansson, Mikael; Andersson, Roger. 2014, SBUF rapport 12851

Acronyms

AEC	Architecture, Engineering and Construction	13
API	Application Program Interface	37
BIM	Building Information Model	2
CFG	Confirmatory Focus Groups	23
CI	Construction Informatics	2
CPM	Critical Path Method	1
CPP	Collaborative Production Planning	20
CVE	Collaborative Virtual Environments	13
DSR	Design Science Research	3
EFG	Explorative Focus Groups	23
HMD	Head-mounted display	13
VPP	Virtual Production Planning	6
IP	Integrated Planning	9
ICT	Information Communication Technology	3
IT	Information Technology	8
LC	Lean Construction	2
LPS	Last Planner System	2
VR	Virtual Reality	12

Contents

“Plans are of little importance, but planning is essential.”
- Sir Winston Churchill

1. Introduction

This chapter introduces the background to the research followed by the identified research problem and gap. The following section contains the research questions as well as a short description of the research design used. The chapter ends with a summary of the structure of the thesis.

The construction industry has during the last decades been characterised by low productivity and increasing specialisation (ter Huurne and Scholtenhuis, 2018), with a fragmented information exchange culture and inefficient work processes (Nepal and Staub-French, 2016). The specialisation and fragmentation have made both the project and onsite production organisations larger, and increased efforts are spent on managing the stakeholders (Bryde et al., 2013; Nepal and Staub-French, 2016). Thus, there is an increased need for communication, collaboration, and cooperation (Erdogan et al., 2008; Gamil and Rahman, 2017), especially in production planning which is considered a central element in project management (Dvir et al., 2003), where the Critical Path Method (CPM) is the dominating planning approach (Olivieri et al., 2019). Even though the industry is seen as proficient in planning, there is still a general problem related to keeping budgets and timeframes (Zwikael, 2009; Christiansen, 2012; Gamil and Rahman, 2017). These problems are partly related to how the organisational culture is manifested in the specialisation and fragmentation, which make it harder to organise (Arditi et al., 2017). These problems are also associated with a lack of transparency in the planning process (Brady et al., 2018).

In a survey about the use of different planning and control systems and their use, classical critical path planning is found primarily used by management positions such as schedulers, department heads, project managers and project engineers (Olivieri et al., 2019). Literature also states that schedules are most often used as documentation (Olivieri et al., 2019). Schedules are often distributed from the planner that merely provides schedules and rarely invites others in the planning process; this highlights the lack of transparency in the process (cf. Winch and Kelsey, 2005; Baldwin and Bordoli, 2014). At the same time, more broadly, planning research has been criticised for focusing on refining current planning processes and emphasising the central specialist planner's role. Thus, the specialist planner's role acts as reinforcing existing hierarchical structures of construction projects (Christiansen, 2012).

A way to improve transparency concerning planning and lessen the effects of fragmentation is the involvement and empowerment of stakeholders such as the contractors own workers and trade subcontractors (Dainty et al., 2002; Brady et al., 2018; Alves et al., 2020). This stakeholder involvement in planning has been shown to reduce guesswork in schedules and improve buy-in and commitment to the agreed schedule and overall understanding of the project (Laufer, 1992; Faniran et al., 1994; Dvir et al., 2003; Winch and Kelsey, 2005; Söderberg, 2006; Simonsen, 2007; Friblick and Olsson, 2009). The involvement of stakeholders is an example of the communicational and social aspects of collaboration in plans and schedules. Through the involvement of stakeholders, the social aspects of the team and team building are emphasised, and the collaboration creates a communicational environment where participants discuss and exchange knowledge. The communicational and social aspects are identified as two kinds of success factors for construction projects in general and have gained increased research attention during the last decade (Erdogan et al., 2008; Xue et al., 2012; Boton and Forgues, 2017; Gamil and Rahman, 2017; Boton et al., 2018; Deep et al., 2019; Turk and Klinc, 2020). Collaborative planning, the act of stakeholders creating the schedule together in a collaborative and social setting, has been developed both internationally as in Scandinavia through, for example, Last Planner System (LPS), (Ballard and Howell, 2004; Schimanski and Marcher, 2020). In Scandinavia, however, there are similar collaborative planning processes are in use by most construction contractors but without the clear Lean Construction (LC) connection (Söderberg, 2006).

With the increased interests in LC, more collaborative and visual approaches to planning and management have been seen (cf. Tezel et al., 2016), such as boards or graphics like plans, schedules, or drawings. A challenge with these tools is to reflect the changing nature of construction sites (Reinbold et al., 2020). Another visual approach developed in parallel with LC is the use of Building Information Model (BIM), henceforth called building models, which has been argued as common ground to communicate around through its information-rich 3D geometry environments. BIM is defined as a collection of functional and physical characteristics, often 3D geometry or 3D models organised in components with metadata, corresponding to specific building objects (Borrmann et al., 2018, Ch.1). Furthermore, building models create engagement amongst the participants and thus improve the understanding of the project complexity (Koskela et al., 2018). This project complexity can be broken down into both the problem of the complex planning task in terms of more technically complex projects and more challenging construction, but also in the organisation of projects' greater number of subcontractors (Gidado, 2004; Winch, 2010; Bryde et al., 2013).

Building models and their use connects to the field of Construction Informatics (CI), the interdisciplinary field of research studying the issues related to processing, representation and communication of construction-specific information for humans and software (Turk, 2006). As such, BIM is perceived as part of CI (Merschbrock and Munkvold, 2012). With the increased general use of 3D models in the construction process, the rise of new ways of communicating complex schedules has appeared in this field. Examples of this are modelling, simulation and visualisation of schedules which can be created, reviewed and simulated through construction process modelling with 3D models or information-rich building models connected to time, also known as 4D models (Heesom and Mahdjoubi, 2004; Eastman et al., 2011; Crowther and Ajayi, 2019).

While 4D models and visualisation predate BIM, and 4D modelling initially was a process of connecting pictures of construction stages together along a timeline, 4D modelling today is more of a modelling process linking 3D objects to a finished schedule (Crowther and Ajayi, 2019). This passive linking has received a critique of lacking interactivity and a more active 4D modelling approach, where being able to utilise the building model better and integrate the 4D modelling into the planning process has been suggested (Boton, 2018; Campagna-Wilson and Boton, 2020). While several tools supporting building models and the passive 4D approach exist, these tools are primarily aimed at expert planners. They need to be more user-friendly to enable a broader use (Crowther and Ajayi, 2019). Available tools also offer little or no support for the development of the 4D schedule during planning sessions, and it is cumbersome to create 4D simulations (Campagna-Wilson and Boton, 2020). In general, there is a lack of collaborative planning and scheduling tools aimed at construction, and the tools existing are aimed at expert and specialist planners (cf. Deep et al., 2019; Campagna-Wilson and Boton, 2020; Dave and Sacks, 2020), and not suitable in collaborative environments. An extensive literature review shows that the BIM and the notion of collaboration could benefit from an increased focus with regards to project management and control aspects since it gains little attention from research (Oraee et al., 2017, 2019). Research also shows that even with the introduction of new tools and processes, users often revert to tried and tested practices (Christiansen, 2012; AlNasseri and Aulin, 2015). Thus, when introducing new software tools and systems, less disruptive ones are usually preferred, as suggested by Turk (2021). Together with the lack of collaborative possibilities, these issues call for user-friendly software to be developed that encourages participants to engage more collaboratively (Fischer et al., 2005; Zhou et al., 2014). These issues further the argument in the literature of the importance of the connection between the users and the Information Communication Technology (ICT) tools, and the highly interdependent interaction between the users and these tools (cf. dos Santos, 1999; Xue et al., 2012; Sackey et al., 2015; Saad et al., 2015; Boton and Forgues, 2017).

This thesis presents a user-friendly collaborative production planning and scheduling system. The system is a web-based multi-user system utilising 3D geometry and information from building models. The system uses a collaborative visual approach to planning and scheduling. Participants can plan, schedule and share knowledge interdisciplinary and information in the system utilises the building model to layer information, reducing the directly visible information and making it available at selection to minimise the extraneous information visible. The system's design, development, and evaluation have followed a Design Science Research (DSR), approach, contributing to how this method could be used and support development in construction informatics.

1.1. Research Problem and Objective

The aim and objective of this thesis are to study a production planning and scheduling process and design, develop and evaluate a user-centric collaborative planning and scheduling system with the use of BIM.

As outlined in the previous section, the problems are often studied as separate fields: BIM, collaborative planning, Lean, communication, or scheduling. The research literature on planning and scheduling focuses mostly on techniques and algorithms(cf. Kenley and Seppänen, 2010; Kim et al., 2013; Koskela et al., 2014; Campagna-Wilson and Boton, 2020; Nwadigo et al., 2021; Alves et al., 2020) and less on actual planning processes and practices. This thesis approaches the challenge of collaborative planning and scheduling in practice from a more integrated perspective. It thus takes a socio-technical point of view, where the human aspects, the artefacts, and the processes are studied. This thesis bridges the gap in research between these dispersed fields of research mentioned above.

This thesis thus investigates a collaborative planning and scheduling process used in practice, then describes the design and implementation of a collaborative planning software system enabling this process to utilise and incorporate the building models. The system is evaluated to validate the support of the collaborative planning and scheduling process and investigate the effects.

1.2. Research Questions

As the thesis aims to enable collaborative planning and scheduling through building models, there is a need to understand the existing collaborative planning and scheduling practice used in the Scandinavian context and how this can be enhanced by integrating building models in the planning process.

Three research questions were identified to address this aim and specify the research objective to apply a DSR approach to the CI field of digitalised planning and scheduling, as below:

RQ 1 *How is a collaborative planning process performed in construction production, and especially in a Scandinavian context?*

RQ 2 *In what ways can ICT for visualisation with building models support collaborative planning and scheduling?*

RQ 3 *What new insights could be gained from integrating building models in the planning and scheduling process?*

The three questions address three stages of the research, the current situation, the design and requirements of an ICT system supporting collaborative planning and scheduling, and what insights the evaluations of such a system could bring. RQ 1 is aimed at identifying collaborative planning approaches in planning and scheduling in construction in general as well as more specifically in a Scandinavian context. Thus, the question addresses the current knowledge base and the more specific application domain, the Scandinavian context where this collaborative planning and scheduling process is used.

While planning theory and collaboration with BIM have been studied separately (Kenley and Seppänen, 2010; Kim et al., 2013; Koskela et al., 2014; Campagna-Wilson and Boton, 2020; Nwadigo et al., 2021; Alves et al., 2020), the combination could benefit from an increased focus with regards to project management(Oraee et al., 2017, 2019; Alves et al., 2020). This research question explores this context and helps to build the foundation for the design and development. The question provides background for identifying requirements for a collaborative planning and scheduling process.

RQ 2 aims to address the design, development and evaluation of the ICT system supporting a collaborative planning and scheduling process. This question is more explorative in its nature and aims to guide the design and development of the ICT system.

RQ 3 is also explorative in its nature, focusing on the developed system and what effects or developments can be identified using the system in the collaborative planning process. The question addresses the contribution of this research, both to the application domain of construction production planning in the form of the developed system and added understanding of collaborative planning and scheduling concepts to the knowledge base. Enabling a comparison and contrast between the planning and scheduling process as practised and the collaborative process developed utilising ICT and building models.

RQ 3 should generate lessons learned that could be applied in the wider construction informatics field. See Chapter 3 for a more in-depth description of the design and relation of the research questions.

1.3. Research Approach

This research follows a Design Science Research (DSR), approach, where the technology in concert with the social aspects in which people operate and interact is addressed. In this context of the CI field of digitalised planning and scheduling, the DSR approach helps build an understanding of how ICT tools can be shaped and developed concerning existing context and processes rather than replace known processes with new ones. Thus, the intention is to keep the process but change the implementation of the process through ICT. First, relevant core theories are identified through a literature review, and then requirements are developed from field observations of the existing planning and scheduling process. From these kernel theories and requirements, a system was designed and developed. This system was then evaluated and evolved through a series of design and evaluation cycles. A more detailed account of the approach can be found in Chapter 3 Research Design.

1.4. Structure of Thesis

The thesis is structured around a DSR approach. The main focus is on exploring a collaborative planning and scheduling process and developing and creating an artefact to be used in a currently existing planning process. The thesis starts with this introduction, then in Chapter 2, background and related work is presented; this presents some collaborative planning approaches to planning common in construction and focuses on the collaborative techniques developed in Sweden and Scandinavia. In Chapter 3, the research design and the use of the DSR approach are explained in more detail. Methods used to collect and analyse data and the studied planning approach is also discussed in this chapter. Then in Chapter 4, the four papers are summarised. An account of the developed artefact, i.e., the Virtual Production Planning (VPP)-system, follows in Chapter 5. The thesis then continues in Chapter 6 with the analysis and discussion around the findings, and then in Chapter 7, conclusions and suggestions for future work are presented.

2. Frame of reference

This chapter introduces the frame of reference for the thesis. It begins with the view of construction planning processes and construction production planning in particular. Then follows the view of construction informatics used in the thesis and a description of building information modelling, digitalised planning, four-dimensional planning and modelling and collaborative environments.

The construction industry has a long-standing reputation for often being late and over budget (Alves et al., 2020; Doloi, 2013). Literature indicates that as little as 50% of activities are finished according to schedule (Baldwin and Bordoli, 2014). These delays and overruns are suggested in research to be associated with organisational culture (Arditi et al., 2017). The organisational culture is manifested in the high specialisation of trades and following fragmentation of the construction industry and especially in construction production (ter Huurne and Scholtenhuis, 2018; Luo et al., 2017). This specialisation creates fragmentation that does construction projects challenging to manage (Bryde et al., 2013). This challenge is put on top of the already busy workday and site managers. Research shows that the site managers daily work over the years has switched from essentially coordinating trades outdoors on-site to more office and administrative tasks (Fraser, 2000; Styhre and Josephson, 2006; Mäki and Kerosuo, 2015). The specialisation and fragmentation increase the need for communication and coordination between trades, but this is challenged by inefficient work processes and a general culture of poor information exchange and communication (Nepal and Staub-French, 2016).

Construction projects face many challenges that affect communication. It ranges from a lack of effective communication between construction parties, communication between ICT-platforms, improper communication channels, and support for advanced communication technologies to differences in education, culture, or team skills.

Simplistically *communication* can be defined as a sender, sending a message, which is acknowledged and received by a receiver in a two-way process (Dainty et al., 2006, ch. 3, p 55). A standard model used to define communication is the Shannon and Weaver model, which started as a technical model to depict the transference of various types of signals from a sender to a receiver, modelled on the electronic telecommunication of messages. This model highlights the importance of noise to the communication process, which can add to and alter the meaning of the sent message(Dainty et al., 2006). The issue of noise in a construction context appears on several levels. Information in construction is still much communicated with drawings, schedules and other paper-based methods (Ratajczak et al., 2017). This highlight the importance of effective communication and messages conveyed between offices, between teams and between individuals (, ibid.). Noise can have different characteristics: for example, physical noise, such as is present at a construction site, or problems with tools used in the communication process, there is psychological noise, noise connected to the psychological state of the sender or receiver, like nervousness or doubt(Dainty et al., 2006, ch3). There is also semantic noise, noise related to how the communication is done, the ”language” of the communication, semantic noise occurs when a technical language of the sender is not understood by the receiver (Velentzas and Broni, 2014).

The specialisation of the industry could introduce this noise in communication through the technical information and language used in different disciplines. Less noise is perceived when this technical language is in a shared frame of reference between the sender and the receiver. This challenge highlights the importance of having a shared frame of reference. The less overlap between frames of reference, the more noise is found in the communication (Dainty et al., 2006, ch3 p 56). In a literature review on factors and effects on communication done by Gamil and Rahman (2017), 33 identified causes of poor communication is found, where lack of effective communication between parties and a lack of effective communication system and Information Technology (IT) platform are the most common factors. The effects of these factors are time and cost overruns and conflicts among parties, to name the top three, but poor teamwork, low productivity, misunderstandings and misinterpretations are also among the 21 effects listed (ibid.). Additionally, Nepal and Staub-French (2016) lifts inefficient work processes related to a culture of poor information exchange and communication as problems. Information exchange, misunderstandings and misinterpretation, could be classified as different types of noise and can be lessened by the collaboration between trade contractors and subcontractors in the projects (Dainty et al., 2006).

Because of the specialisation and fragmentation, knowledge and competence are individual, with experience differing from person to person (Büchmann-Slorup and Andersson, 2010; Saad et al., 2015). Planning and production control is an approach to handling different trade competencies and reducing the organisational complexity created by this fragmentation (Dvir et al., 2003). Nevertheless, even though planning and scheduling are seen as core aspects of construction production management (Al Nasseri et al., 2016; Winch and Kelsey, 2005; Nwadigo et al., 2021), the challenges of differences in viewpoints between general contractors and trade subcontractors are prevalent (Dave and Sacks, 2020). One way to define planning and scheduling is that planning is regarded as the decisions taken regarding objectives and tasks of the project, while scheduling is the process by which the plans are prepared, sequenced and presented to stakeholders (Baldwin and Bordoli, 2014), this is the approach taken in this thesis.

The research literature on planning and scheduling focuses mostly on techniques and algorithms(cf. Kenley and Seppänen, 2010; Kim et al., 2013; Koskela et al., 2014; Campagna-Wilson and Boton, 2020; Nwadigo et al., 2021; Alves et al., 2020) and less on actual planning processes and practices. According to Alves et al. (2020), this has been the problem since the problem was discussed in Laufer and Tucker (1987) until today. San Cristóbal et al. (2018) argues along this line, where investigations in new methods for planning, scheduling and control are suggested. Daniel et al. (2020) goes further and argues that successful adoptions of collaborative approaches in other industries could give inspiration on how to move from focusing on technology implementation solely to a more social approach to project management, an approach that encourages collaboration and where stakeholders and technology are considered in concert.

2.1. Collaborative planning approaches in construction

Collaboration in construction planning is often seen in a lean construction context, with a focus on the last planner (Ballard and Howell, 2003; Zhang et al., 2018; Daniel et al., 2016; Sacks et al., 2010). However, collaboration in construction, in general, has steadily gained interest over the last decade (Deep et al., 2019), and Turk and Klinc (2020) argues that social elements of collaboration should be integrated into organising and managing work. Alves et al. (2020) furthers this and argues that a better understanding of current practice, the practitioner's perspectives on planning and scheduling, and the root causes for changes in practice will enable change toward more collaborative scheduling practices in general. Furthermore, Alves et al. (2020) argues that collaboration improves schedules and thus positively affect cost and performance aspects of projects. Similar arguments are given by Arditi et al. (2017), where a collaborative setting in the organisational culture could help alleviate delays. Deep et al. (2019) concludes in a review that 'trust, commitment and reliability will further collaboration and thus enhancing project productivity. This ties into research on empowering the sub-contractors and workers, the effects of the fragmentation of the construction organisation seem to lessen (Dainty et al., 2002). The involvement of subcontractors in the planning also helps to reduce the complexity of the project. Through involvement, a common and shared understanding of the project can be discussed and understood (Dvir et al., 2003; Faniran et al., 1994; Friblick and Olsson, 2009; Laufer, 1992; Simonsen, 2007; Winch and Kelsey, 2005). Another effect of engaging forepersons and workers from the trade subcontractors in the planning is that they take ownership of the schedule and commit to their agreed work (Daniel et al., 2014; Lindholm, 2014). This type of collaboration and engagement can be seen in Sweden and Scandinavia due to a generally collaborative culture, with low-power distance (Bröchner et al., 2002; Elfving, 2021).

A formalised type of collaborative planning process was developed in Sweden during the late 1980s as an agreement between the Swedish construction worker union and the contractors and employee organisations in the construction industry as a step to utilise experience and knowledge from the workers better (SAF et al., 1986). From this, the Integrated Planning (IP), approach was developed and adopted, but a lasting implementation does not seem to be documented (Söderberg, 2006). A core component in IP is collaborative planning, where the production of different schedules are collectively developed and agreed upon, but using otherwise traditional planning concepts such as the Critical Path Method (CPM), ultimately visualising schedules as bar charts (Söderberg, 2006). The introduction of IP in the 1980s coincides with the increased interest in quality in construction(Bröchner et al., 2002), and in lean manufacturing methods worldwide in the manufacturing industry (Liker, 2005).

Lean Manufacturing inspired the Lean Construction (LC), movement and resulted in the late

1990s in lean based production processes (Sbiti et al., 2021; Friblick and Nordlund, 2013). The Last Planner System (LPS) is one of the core approaches in LC, created as a reaction to the traditional CPM, approach (Patricia Tzortzopoulos, Mike Kagioglou, 2020, Ch.3). LPS tries to limit the details of high-level schedules such as the master schedule to milestones to reduce overplanning in uncertain early phases of the project. At the lowest level, the phase closest to production, the schedule is detailed using the forepersons from the trade subcontractors as last planners, hence the name (Ballard and Howell, 2003; Daniel et al., 2016). LC research is widely spread throughout the world, with UK and USA having central roles in the lean network with a wide set of researchers and companies active in LC (Li et al., 2019). According to some researchers, actual use of LPS is still low and has a way to go to become established and widely adopted (Daniel et al., 2015; Lagos et al., 2017). Patricia Tzortzopoulos, Mike Kagioglou (Ballard in 2020, Ch.3) indicates that several industry practitioners have started their Lean journeys with the adoption of LPS, some even stating that LPS was the most successful lean method implementation. Furthermore, research has found that the high project orientation and relatively high decentralised decision power on project level imply that the most effective implementations of Lean methods are through a balanced approach, where pilot projects build interest. However, top management ensures that standardisation and ”best practice” are communicated centrally (Elfving, 2021). LPS type of implementations are beginning to spread and is exemplified in Scandinavia with implementations in Finland (Kenley and Seppänen, 2010; Elfving, 2021), in Danish production Simonsen (2007) and primarily in the design phase and industrialised construction in Sweden (Tjell, 2016; Kifokeris, 2021).

The LC approaches often entail visual management aspects, whether in the physical form of boards or graphics like plans, schedules, or drawings. A challenge with these tools is to reflect the changing nature of construction sites (Reinbold et al., 2020). It has been shown that recording data in visual management systems leads to a greater understanding of the underlying data and, in turn, the project amongst the participants (Tezel et al., 2009). While some visual tools are more geared towards production and process management, others exist for more general performance, quality and knowledge management (Tezel et al., 2016). Examples of production and process management tools could be charts for visual control, like kanban boards or visual signals, several of which have been digitalised (Urbina Velasco, 2013; Lin and Golparvar-Fard, 2021).

2.2. Information Communication Technologies and Construction informatics

The use of ICT systems in construction is regarded as a subfield of Construction Informatics (CI). CI is the interdisciplinary field of research, filling the gap between computer science, construction and construction management. CI studies issues related to processing, representation and communication of construction-specific information in humans and software (Turk, 2006, 2007;

Isikdag et al., 2009; Merschbrock and Munkvold, 2012). A system in this context is defined as interdependent, interacting parts that combined form a whole (Arnold and Wade, 2015), i.e. a set of methods, combined as a process which is applied through, e.g. a software. CI literature calls for a development of common standards and protocols for construction ICT, especially with regards to interdisciplinary human-computer interaction, computer-mediated human-to-human interaction and integrations of visualisation in various interfaces (Lu et al., 2015). Research has a strong focus on tools and developing digitalisation, but organisations in the construction industry struggle more with human and organisational matters (Moscati and Engström, 2019). Moscati and Engström (2019) also indicates that there seems to be a shift from more technical concerns toward social and economic aspects. Building Information Model (BIM), are a common component in many of the technologies that are meant to facilitate construction processes today (Davies et al., 2015; Davies and Harty, 2013), as such BIM can be perceived as part of CI (Merschbrock and Munkvold, 2012). Crowther and Ajayi (2019) shows that BIM has helped construction projects to move towards more collaborative approaches, thus touching at the more social aspects of construction projects. More collaborative approaches could help the social context of construction through the improvement of the information exchange and communication problems that is an acknowledged challenge(Nepal and Staub-French, 2016).

2.2.1. Building Information Modelling and 4D modelling and visualisation

BIM is defined as a collection of functional and physical characteristics, often 3D geometry or 3D models organised in components, with non-physical hierarchies such as spaces and zones. Objects, spaces and zones can be populated with data such as materials, types and technical properties (Borrmann et al., 2018, Ch.1). The adoption of BIM is most prevalent in the design phase of projects and less common during the construction phase or the facility management phase (Linderoth, 2013; Ghaffarianhoseini et al., 2017; Svalestuen et al., 2017). More specifically, in the construction phase, the BIM use has been studied in on-site construction projects in Sweden in a series of bachelor and master theses, which concluded that use is limited primarily to visualisations and clash detection (Sundquist et al., 2020). To some extent, the lack of use amongst sub-contractors can be traced to lack of education in the BIM software as well as lack of knowledge that there were BIM models available (ibid.).

BIM and Lean concepts have been linked in research and shown to enhance their respective benefits if adopted alongside each other, such as in increased collaboration (Bhatla and Leite, 2012; Khanzode et al., 2006). Some literature highlights BIM as having the potential to help increase efficiency, productivity, and performance. (Dainty et al., 2017) One of the more common uses of BIM and building models, apart from the pure visualisation, is construction process modelling, also known as 4D modelling (Borrmann et al., 2018, Ch.1). This type of visualisation acts as visual communication, which according to Formoso et al. (2002), increases participants engagement in the project. The literature shows that even though 4D offers potential advantages in, for example, the planners' communication of the schedule (Eastman et al., 2011, Ch.6), or through construction process simulations and animations (Borrmann et al., 2018, Ch.18), it still lacks widespread adoption (Crowther and Ajayi, 2019). The lack of adoption is argued by Büchmann-Slorup and Andersson (2010) to be related to the missing involvement of subcontractors, suppliers, and manufacturers. Another possible hindrance is the currently available software for developing 4D construction schedules or simulations, which demands schedules and models to be developed to a similar level to facilitate the linking of schedules and objects. Campagna-Wilson and Boton (2020) and Tulke and Hanff (2007) shows this by arguing that the available tools still requires significant effort to link created schedules to building models to produce the 4D simulations. The lack of standardised processes and methods for creating the 4D simulation in parallel with preparing the construction schedule is one of the significant limitations in the current implementation of 4D simulations according to Campagna-Wilson and Boton (2020).

2.2.2. Virtual Reality and Collaborative Virtual Environments

Building models and their use of 4D simulations are considered part of Virtual Reality (VR). The term VR is within the scope of the thesis follows the definition by Johansson (2016), who defines VR as a computer-generated visualisation of spatial data which a user interactively controls. Furthermore, VR is primarily seen in the design phase at the moment, with some initiatives reported during the construction phase. Typical applications for desktop and immersive VR in construction is site layout planning, construction safety planning and safety training and walkthroughs and reviews (Azhar, 2017; Hafsia et al., 2018; Getuli et al., 2020; Muhammad et al., 2020). The types of VR considered in the thesis is primarily *real-time walkthroughs and reviews* either for reviewing the construction project at hand or for exploring and understanding specific information in the project.

VR use in the design phase is reported by Roupé et al. (2019) to allow stakeholders to understand the project better. Furthermore, it enables the users to move from passively interpreting documents and the design to a more active co-designing role. This move of the users' role is exemplified in the case of design review sessions, where previous studies show that VR can clarify many aspects of the design that is difficult to comprehend from traditional design documents, such as clashes and lack of space for installations and maintenance (Roupé et al., 2016; Zaker and Coloma, 2018). Here the knowledge that is hard to extract from participants, experience and insights gained over the years in the industry, the tacit knowledge, can be discussed concerning the visualisations through simulations. VR has also been found to reduce ambiguity in interpreting construction intent through 3D compared to more traditional 2D documentation and drawings. With the use of 3D, the user does not have to internally visualise and interpret the documents (Roupé et al., 2019).

4D simulations are a typical use of desktop VR. With 4D modelling, required 3D data can be gathered directly from building models, which somewhat eases the process of creating 4D simulations. However, the creation of 4D models still lacks a standardised and formalised format but approaches to these through constructability analysis using VR, BIM, and 4D visualisations have been presented in Boton (2018).

Furthermore, the increased use of building models in the Architecture, Engineering and Construction (AEC) industry and VR during the design phase, coupled with new generations of affordable Head-mounted display (HMD)s, have resulted in the industry gradually adopting more immersive VR (Roupé et al., 2019). The use of immersive VR and HMDs can be seen in workspace planning, health and safety planning (Getuli et al., 2020), offsite introduction to new projects and design reviews (Roupé et al., 2019; Wolfartsberger, 2019). The use of HMDs allows stakeholders to ”step into” the model on a real-world scale and experience the project in scale 1:1 and thus better understand challenges and design intent (Roupé et al., 2019). Also, it has been found that participants who work in service and maintenance prefer using VR to using desktop **CAD!**/BIM viewers. This preference is traced to VR being seen to resemble better their natural work environment (Wolfartsberger, 2019)

When it comes to different types of VR at the construction site, this has been studied in a series of research projects conducted between 2014 and 2021 (Johansson et al., 2014; Johansson, 2016; Roupé et al., 2016, 2017; Johansson and Roupé, 2019, 2021). These studies aimed to use VR as a user-friendly interface to the BIM to help construction workers and site personnel explore, review, and understand the project and different work tasks better with similar conclusions as in design reviews mentioned earlier. 4D simulations in immersive VR has also been shown in prior research (Boton, 2018), but it has been found to need better support for collaborative and interactive 4D modelling to go from passive consuming of simulations to active modelling and redefinition of 4D schedules.

In general terms, tools, especially 4D and scheduling tools, need expert users to aid the workers, which creates a barrier for usage (van Berlo et al., 2015; Chowdhury et al., 2020). Research regarding the development of collaborative tools calls for a more holistic, socio-technical approach, where the tools are developed to support and encourage the individuals to engage collaboratively (Fischer et al., 2005; Zhou et al., 2014), focusing on interactions between people and technology as well as the work processes applied (Fischer et al., 2005; Sackey et al., 2015). These tools can be considered part of the broader field of Collaborative Virtual Environments (CVE), used in the more general development of ICT systems to approach the facilitation, development and collaboration across different stakeholders or participants.

A system that facilitates a shared understanding through collaborative scheduling exemplifies the social and creative processes stipulated in CVE literature. In CVE development, the focus is on creating awareness, and a shared understanding of each other’s work, providing mechanisms to draw out tacit knowledge and thus help the users better understand the problem. A shared understanding can be achieved through a shared context between several users (ibid.)

This shared context should also provide possibilities for collaborative work, both simultaneous, in parallel and serially, building upon each other's work (Fischer et al., 2005). This shared context also stipulates a need to be able to transition from individual work to shared collaborative work (Snowdon et al., 1998). The CVE literature also highlights the importance for users to have possibilities for personal reflection space as well as collective exploration and action space (Fischer et al., 2005). These spaces can be facilitated through flexible multiple representations and visualisations, tailored to different needs, tasks and users (Snowdon et al., 1998). As communication is a big part of collaborative work, there is also a need to provide possibilities in reality or VR for face-to-face communication, conversations, gestures, postures, and facial expressions to be communicated (Snowdon et al., 1998).

The goal for CVE is to guide the creation of tools promoting collaboration and participation, where stakeholders can actively contribute rather than having passive consumer roles (Snowdon et al., 1998; Fischer et al., 2005), which fits with the objective of collaborative planning and scheduling with 4D and VR.

3. Research Design

This chapter describes the research approach of the thesis. The chapter describes how the Design Science Research approach is applied to collaborative planning and scheduling within the construction informatics field. It then motivates and describes the methods used to collect the data that the thesis is based on.

In this research, I have contributed to the field of CI, and more specifically within collaborative planning and scheduling. The scope of my research is limited to construction planning practice and the methodologies and technology that support this. Through interviews with practitioners, observations of collaborative planning methods, and the design, the development and evaluations of a novel collaborative planning system, I address the complex interaction of ICT, the planning and scheduling and the social context where this ICT system is manifested. Thus, the research uses the Design Science Research (DSR), paradigm to design the research project. DSR differs from natural science and social sciences in such a way that DSR aims to create things that serve a human purpose, rather than merely trying to understand reality (March and Smith, 1995; Simon, 1996). The interplay of practice, process and people highlights the socio-technical aspects of DSR, where not only the development of the artefact is discussed, but also the context where the artefact is applied becomes relevant to the research (Carlsson et al., 2011).

Johannesson and Perjons (2014) defines a socio-technical system concerning DSR:

> *"a hybrid system that includes technical artefacts as well as humans and the laws, rules, and norms that govern their actions."*

The thesis uses a socio-technical view addressing system development from a perspective where both the technology in concert with the social aspects in which people operate and interact is addressed (cf. Sackey et al., 2015). Thus, the problem in the thesis is approached from the context of the practice through observations.

DSR is traditionally focused on the development of an artefact. An *artefact* is an object made by humans, designed to address a practical problem. Artefacts can range from physical objects, drawings, descriptions and more, to methods and guidelines that support people in processes. March and Smith (1995) defines an *artefact* as a construct, a model, a method, or an instantiation. Hevner and Chatterjee (2012, ch. 1, p 6) adds better design theories to the list to highlight the addition of knowledge as a contribution to the field. A *set* of constructs can be defined as the language by which shared knowledge is communicated (March and Smith, 1995). Models are defined as descriptions or representations of how things are, while methods are formalised instructions or a set of steps to perform a task. *Instantiations* are artefacts realised in their environment. Instantiations make use of constructs, models, and methods, but instantiations can also be developed and thus, constructs, models and methods can be derived from its use (March and

Smith, 1995). DSR may use a local problem and practice to solve a problem. However, the artefact and knowledge created while designing the artefact should be interesting in a more general practice (Johannesson and Perjons, 2014).

This thesis exemplifies the study and development of a method through the observed planning approach. At the same time, the developed artefact is the instantiation of the constructs and methods using the planning approach to realise the end-product of the artefact.

March and Smith (1995) defines two main design processes as part of DS research: build and evaluate artefacts. The purpose of DSR is to produce and communicate design knowledge that is of general interest, and this contrasts to design work that is more localised and thus may produce solutions that are less relevant in a broader context and contribute no new knowledge (Hevner et al., 2004; Johannesson and Perjons, 2014). The distinguishes DSR from routine development and design, which would be applying best practice without developing any new knowledge (Hevner and Chatterjee, 2012, ch. 1, p 7). Routine design is typically not a valuable DSR contribution since it only offers incremental innovation to known solutions and produces no new general-interest knowledge to the field. To more clearly show a contribution to the studied field Gregor and Hevner (2013) suggests a two-dimensional positional classification of DSR. See Figure 3.1, where the axes are made up of solution maturity and application domain maturity.

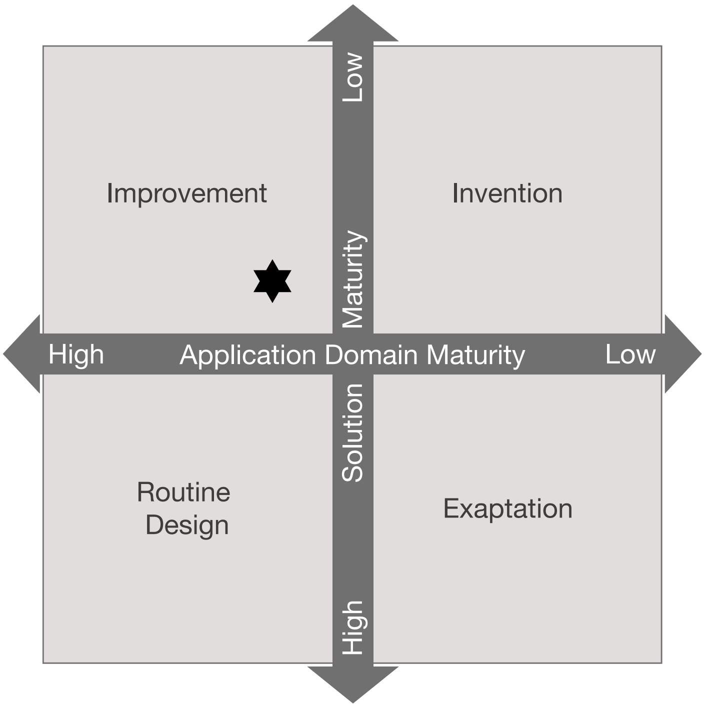


Figure 3.1: The contribution of the thesis as improvment, superimposed on the diagram of the different types of design contributions adapted from Gregor and Hevner (2013).

These contributions result in four general fields where each of the dimensions goes from high to low, as seen in Figure 3.1. Suppose a high application domain maturity is combined with a high solution maturity. In that case, the problems in the field are well known. They have many known solutions, and this is just an application of best practices with little or no significant scientific contribution. The diagram in Figure 3.1 puts high solution maturity and high application domain maturity in the lower-left corner, represented by routine design. Above routine design in the diagram improvements is found, where solution maturity declines but still has high application domain maturity. *Improvements* are defined as new solutions to known problems and contribute to an existing problem that is improved upon compared to state of the art, and thus constitutes a valuable scientific contribution compared to routine design. Exaptations are situated directly to the right of routine design. Solution maturity is high, but application domain maturity is declining, enabling existing solutions to new problems. Inventions are the rarest of design science contributions, as inventions are new solutions to new problems (Gregor and Hevner, 2013).

This research and the developed artefact improve on current planning and scheduling solutions, adding the interactive, collaborative aspects and the direct coupling with the building model. The positioning of the system can be seen in Figure 3.1. The system is classified as an improvement since it improves a current planning practice from a high application domain maturity, combining it with collaboration rather than routine design in that the designed artefact improves current planning practice, which can be seen as a state of the art what is used in practice.

3.0.1. Research questions and DSR approach

The research approach, using DSR, incorporates the three research questions from Section 1.2 in the framework developed by Hevner et al. (2004), with the main activities of DSR defined as the design, build, and evaluate activities. This framework is extended with three cycles, where the design cycle is one, and the two remaining cycles are the relevance and rigour cycle (Hevner, 2007). These cycles are used to explain the relation of research to its environment, the application domain it is used in, and the knowledge base, the academic foundation of the field of knowledge. These can be seen in Figure 3.2.

The relevance cycle ensures that the research context is performed in a localised context and relevant to the problem at hand. Here requirements and acceptance criteria are set and acts as input for the development of the artefact. The output is then returned and tested in the appropriate environment against the acceptance criteria. On the other hand, the rigour cycle builds upon the existing knowledge base in the application domain of the research. A properly performed rigour cycle identifies state of the art and existing artefacts and processes. Here, additions to the knowledge base consist of extensions to original theories and methods, the new artefact as design products or processes, and the experience gained from developing and field testing the artefact in the application environment.

These three cycles seen in Figure 3.2 form the frame for how the research in this thesis has been designed. As DSR is iterative, there is no linear progression but loops within loops that feed

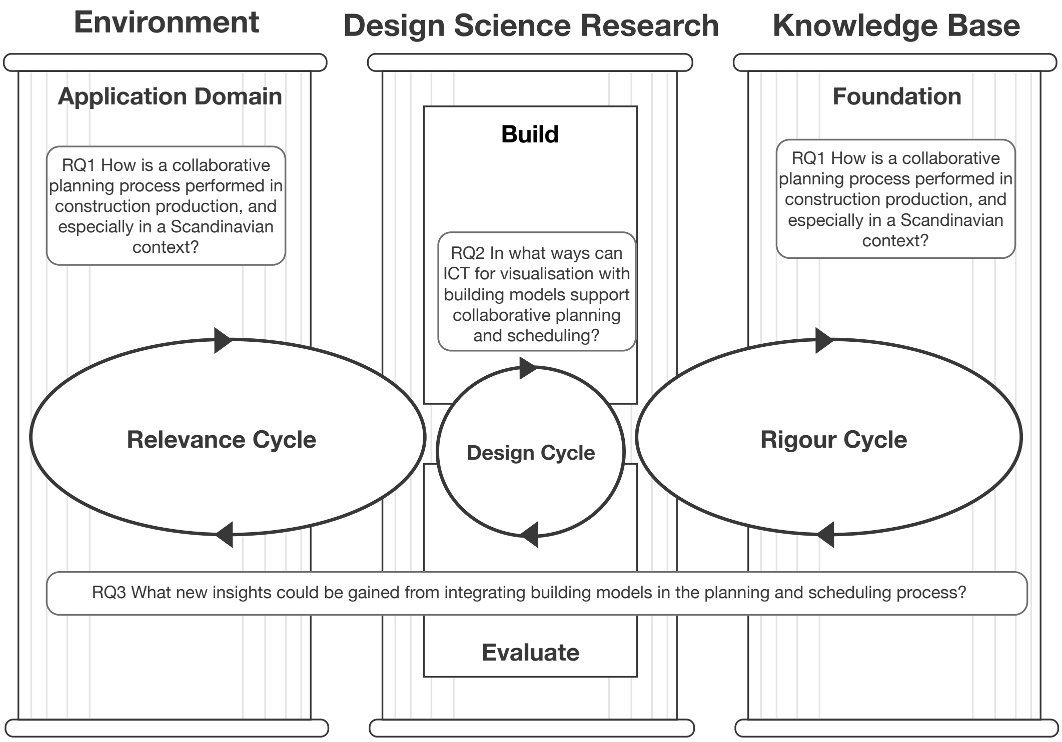


Figure 3.2: DSR cycles, adapted from (Hevner, 2007) with research questions superimposed.

each other. The progression will first be described through how the research questions related to the DSR process. This process is manifested in the four appended papers, which somewhat represent iterations and cycles of development and evaluations of the artefact. The design cycle is the heart of the DSR research and symbolises the rapid iterations in the design work of the artefact. Requirements are drawn from the relevance cycle and coupled with the design and evaluation theories and methods drawn from the rigour cycle.

RQ 1 addresses the application domain, current practice in the industry, the knowledge base and the position of the literature on collaboration, planning and scheduling. Thus, posing questions in both the relevance cycle, as seen in the left part of Figure 3.2, as well as the rigour cycle, in the right part of the previously mentioned figure, drawing on planning theories, BIM, as well as collaborative work and communication theories. This question helps identify the elements of the collaborative process and evolves the requirements for the development of the artefact, which leads to the second question.

RQ 2, aims to explore the design and building of an artefact to enhance the collaborative planning and scheduling process, drawing knowledge form RQ 1 concerning design requirements, which forms the acceptance criteria that are used for evaluation of the artefact. With these requirements as a basis, a design is developed and then evaluated against these requirements. Thus, RQ 2 could be said to represent the primary design-build-evaluate cycle of DSR.

DSR aims to contribute both a practical solution to the problem and a contribution to the knowledge base. Here, balancing relevance and rigour in the design cycle ensures that the research contribution to the application domain knowledge base is firmly based in practice. Thus, the rigour and relevance are ensured (Hevner, 2007). RQ 3 uses the evaluations to gather contributions, judged on relevance for the application domain and rigour towards the foundation. The question stretches over all three columns and respective environments, as illustrated in the lower parts of Figure 3.2.

3.1. Research process

To address these questions and the cycles in DSR, the research has progressed in loops. This thesis and the appended papers consist of several design cycles intertwined with a set of rigour and relevance cycles. The design science (DSR) research presented uses a problem-solution approach, with a produced artefact as one of the main contributions of the research. The design, development, and evaluation of the system, the DSR approach, also contributes to how this type of method could be used for and support development within construction informatics.

Problems in DSR are identified from the environment, see Figure 3.2. The problem in this research was initially formed by a project planner employed at one of the largest construction companies in Scandinavia. The planner realised that their collaborative planning process for production planning was beneficial for the project. Much less time was spent trying to convince stakeholders of the schedule, and fewer adjustments were made. The planner contacted the researcher and a couple of the researcher's colleagues to ask about a possible development of the collaborative planning sessions. During discussions around the planning method and its practice, the potential to use a more visual approach than just digital sticky notes was identified. During these discussions, it was noticed that the building models were only used for the visual representation, and the information they contained could help solve issues during the planning sessions.

From this problem, the research questions seen in Section 1.2 were derived. DSR was chosen as the preferred research strategy with its focus on the problem-solution approach. The thesis addresses the requirement formulation, design development and evaluation of a collaborative planning and scheduling system based on observed planning practice. Thus, using the definitions above with March and Smith (1995), this thesis is mainly concerned with the planning processes, in DSR referenced as the models which are manifested in the collaborative planning approach studied as constructs making up a model for the collaborative planning process. The thesis results in an instantiation in the form of the developed artefact resulting from the research project encompassing this thesis.

3.1.1. Methods of data collection and analysis

The DSR approach taken in this thesis needs to build on a solid foundation of the current situation, both in terms of current practice and in the knowledge-base literature review, capturing the state of the art of the body of knowledge. Thus, the design of the data capturing was done through three distinct methods. The research was initiated with seven semi-structured interviews in parallel with the literature review and followed by seven observations in four different projects of the same Collaborative Production Planning (CPP) process. This research design conforms to the recommendation to capture context and the knowledge base (cf. Hevner, 2007; Johannesson and Perjons, 2014). The developed artefact was evaluated using four different projects through fifteen evaluations of the developed Virtual Production Planning (VPP), system. A summary of the observed projects can be found in Table 3.1 and an overview of the observations in Table 3.2.

Interviews regarding how disciplines approach planning.

As an initial insight into how different disciplines and subcontractors reason around their project planning, a small set of participants were selected from site management and the subcontractors. The aim was to gather preliminary insight into the different disciplines approach to information and how they planned their activities. The interviews were held with workers and forepersons (the subcontractors leading representative at the construction site). The participants represented the major subcontractors of a typical construction project and were distributed as follows:

- One project planner
- One site manager
- One foreperson from the electrical subcontractor
- One foreperson from the plumbing subcontractor
- One foreperson from the Prefabrication subcontractor
- Two workers, whereas one was foreperson from the sprinkler subcontractor
- Two workers from the Heating, Ventilation and Air-conditioning subcontractor

The choice to keep these interviews semi-structured allowed for a more relaxed and explorative interview, allowing the interviewee to talk more freely (Kvale, 1996). Thus, the interviews followed an interview guide, where the interview questions were mainly concerned with planning and information gathering related to planning in the project. The questions touched upon the following subjects:

- what kind of information they used,

- what kind of information they needed to perform their tasks,
- if they used information from other disciplines to understand the project,
- if they used information from other disciplines to solve specific tasks of their own,
- if they missed information at the current state to be able to perform their tasks.

The interviews were conducted with three researchers, one leading the interview, one taking notes, and one supporting in both tasks, enabling cross-validation of the interview analysis. The duration of the interviews varied between 20 and 45 minutes each, and the interviews were recorded with the participants' consent. The results from the interviews were transcribed and coded and helped form an insight into what information workers could be interested in during the planning and scheduling of their tasks.

Observations of the Collaborative Production Planning process.

The observations of the collaborative planning sessions were the most substantial part of the data collection, apart from the evaluations. The observations were vital to gather insights into the current practice of the CPP, process and how it was implemented and used. Thus the observations of the collaborative planning sessions were vital to contextualise this DSR-project in its environment.

With insights from the interviews on how participants could view their planning and scheduling process and need for information, observations were planned to observe this in practice. The participants were observed doing their work packages in their planning sessions by going through available material, primarily drawings and descriptions. The observations were conducted throughout the seven years of the research project, as seen in Table 3.1. This spread helped gather requirements essential in DSR for the development of the artefact as they define the evaluation criteria with which the artefact is to be evaluated. By doing three sets of observations, the initial requirements could be validated by linking the observations, and possible new requirements could be identified and decided.

The observations helped to form an understanding of how knowledge is represented in individuals, documents, routines and the underlying technology (cf. Johannesson and Perjons, 2014). Thus, the observations helped identify how the artefact should represent knowledge and how this affects the organisation and the routines (ibid.). Dix et al. (2004) states that the requirements identification aims to find the workflows that are suitable to automate, which is done through the observations described here. These requirements need to be compared and gathered with identified process elements from the knowledge base in the literature.

After the initial three observations, done in project OP1 as seen in Table 3.1, a preliminary understanding of the practice and use of the CPP process was gained. These observations also informed the initial design cycles of the DSR project and were compared with a fourth observation

Table 3.1: Observations and project types

No.	Project type	Where	Proj. no.	When
1	Commercial bulding	Project office, Western Sweden	OP1	2014
2	Commercial bulding	Site office, Southern Norway	OP1	2014
3	Commercial bulding	Project office, Western Sweden	OP1	2014
4	Public bath	Head office, Gothenburg, Western Sweden	OP2	2017
5	Commercial bulding	Site office, Western Sweden	OP3	2018
6	Commercial bulding	Site office, Western Sweden	OP3	2018
7	Hotel and Office	Site office, Gothenburg, Western Sweden	OP4	2019

of a new project organisation with a different project, OP2, and a different construction company. Observations number five and six, as seen in Table 3.1, were conducted with project OP3, a project similar to the OP1 and helped reach saturation in the understanding of the CPP process in practice. OP3 also shared large parts of the project organisation with OP1 and was one of the last projects in a sequence of projects negotiated with a client to be built in Scandinavia. The last observation was used similarly to the fourth observation, with a new project and a new organisation to observe how other site managers implemented the CPP process. In total, seven observations were conducted during the research project to gather more insight into collaborative planning and scheduling as used in practice. The projects the observations were conducted on are summarised in Table 3.1.

The use of repeating observations enabled a broader set of types of projects, project organisations and companies employing the CPP process to be studied. Through this repeating set of observations, it was possible to find and validate processes and phenomena seen in different types of projects and organisations and come closer to the principles of the CPP process itself.

To gain practical insights into the practice of the collaborative planning process and the principles of the CPP process, the researcher joined as observer-as-participant, where the researcher declares the intention of the observation and is open about the role as a researcher while still participating in the work (Bryman and Bell, 2011, ch. 17, p 437). In these sessions, the researcher's role was as a BIM-Specialist to aid the session with navigation and use of the building models, mainly in the review and walkthrough of the projects. A thorough understanding of the context, the CPP process as practised, was gained from participating as participant-as-observer. It also highlighted the participants' confusion and the complexity of the planning process and information digestion related to this.

The selection of projects using the CPP process was limited to projects involving a specific project planner to ensure that the use of the CPP process was consistent. The researcher's immersion was complete during the observations. The timeframe was somewhat limited, with the most lengthy observations lasting about a whole day. These observations were summarised in field notes, taken during breaks and after the sessions (cf. Bryman and Bell, 2011, ch. 17, p 444). The field notes and the observation data were codified and thematised by grouping observations and reflections in general themes, which later was refined and re-thematised. The analytical framework used to thematise the observations and interviews was based on the socio-technical view presented in Chapter 1, with dimensions such as people, processes and technology (cf. Prodan et al., 2015; Liu et al., 2017). The primary outcome was challenges identified in the current planning process and the general requirements needed to be performed.

Evaluations of the Virtual Production Planning system

As the design works are incremental and cyclical and DSR relies on the Design-Build-Evaluate design cycle, the artefact developed has undergone several stages of development and types of evaluations. The strategy of the design of the VPP, system was to get the system useable through small iterations and evaluations focusing on the technology and the functionality. The initial evaluations used Explorative Focus Groups (EFG)s (cf. Hevner and Chatterjee, 2012, ch. 10), where the EFGs are used to improve the VPP-system design incrementally. These evaluations thus focused more on the specific functionalities and improvements of the developed application. The EFGs were followed by Confirmatory Focus Groups (CFG)s. The CFGs studied and demonstrated the utility of the VPP-system in a setting close to the original CPP process. The CFG evaluation thus focused more on the overall process, taking into account the social context of users, process and technology.

Table 3.2 lists the types of evaluations in the third column. At the moment, the system is at version 1.7.4, where the 1 is a major version, the 7 is a minor version, and the 4 represents bugfixes and such of the minor version, Table 3.2 shows which version of the artefact was used at each evaluation.

Table 3.2: Evaluations

Number	Participants	Type	Project type and no.	Prototype	Duration	Media
1	5 Middle managers, 3 Project planners 3 Researchers	Explorative	Office building, EP1	v0.5		Written notes
2	1 Project Planner, 3 Researchers	Explorative	Office building, EP1	v0.8	03:04:18	Audio
3	8 middle managers, 3 Researchers	Explorative	Apartment blocks, EP2	v0.9	00:15:19	Audio
4	3 CM Students, 1 Researcher	Confirmative	Apartment blocks, EP2	v0.9.5	01:40:59	screen recording + video + audio
5	3 CM Students, 1 Researcher	Explorative	Apartment blocks, EP2	v0.9.5	00:55:45	screen recording + video + audio
6	2 CM Students, 1 Researcher	Explorative	Apartment blocks, EP2	v0.9.5	01:08:55	screen recording + video + audio
7	1 Project Planner, 2 Researchers	Explorative	Apartment blocks, EP2	v0.9.9	01:35:35	video
8	20 Project planners, 1 Researcher	Explorative	Apartment blocks, EP2	v1.1	01:00:00	Written notes
9	5 Middle managers, 3 Researchers	Explorative	Apartment blocks, EP2	v1.2	02:00:00	Written notes
11	1 VDC-manager, 3 Researchers	Explorative	Apartment blocks, EP2	v1.3.6	00:25:17	Zoom video recording
12	2 Middle managers, 3 Project planners 3 Researchers	Explorative	Apartment blocks, EP2	v1.3.9	01:01:37	360 Video
13	6 VDC-managers, 3 Researchers	Explorative	Apartment blocks, EP2	v1.4	00:58:13	360 Video
14	1 Site Manager, 2 Project Planners, 3 Researchers	Confirmative	Office & hotel building, EP3	v1.5.7	01:55:33	Zoom video recording + 360 Video
15	1 Deputy Site Manager, 1 BIM specialist, 1 BIM Strategist, 3 Researchers	Confirmative	Office building, EP4	v1.7.4	02:15:30	Zoom video recording

The table also shows information about each of the 15 significant evaluations conducted. The table only depicts more systematic evaluations where more than 2 participants have taken part. Many more evaluations were done but may be seen as more routine evaluations of certain minor aspects of functionality. All evaluations except two were recorded with either audio recordings or audio and video, with consent from the participants. These recordings allowed for a deeper analysis and re-experience of the evaluations, gathering essential insights from the participants. Later evaluations also used 360 video recordings and cameras, which literature exemplifies as often less intrusive to capture the whole rum and place the researcher back in the room with the evaluators (cf. Reyna, 2018).

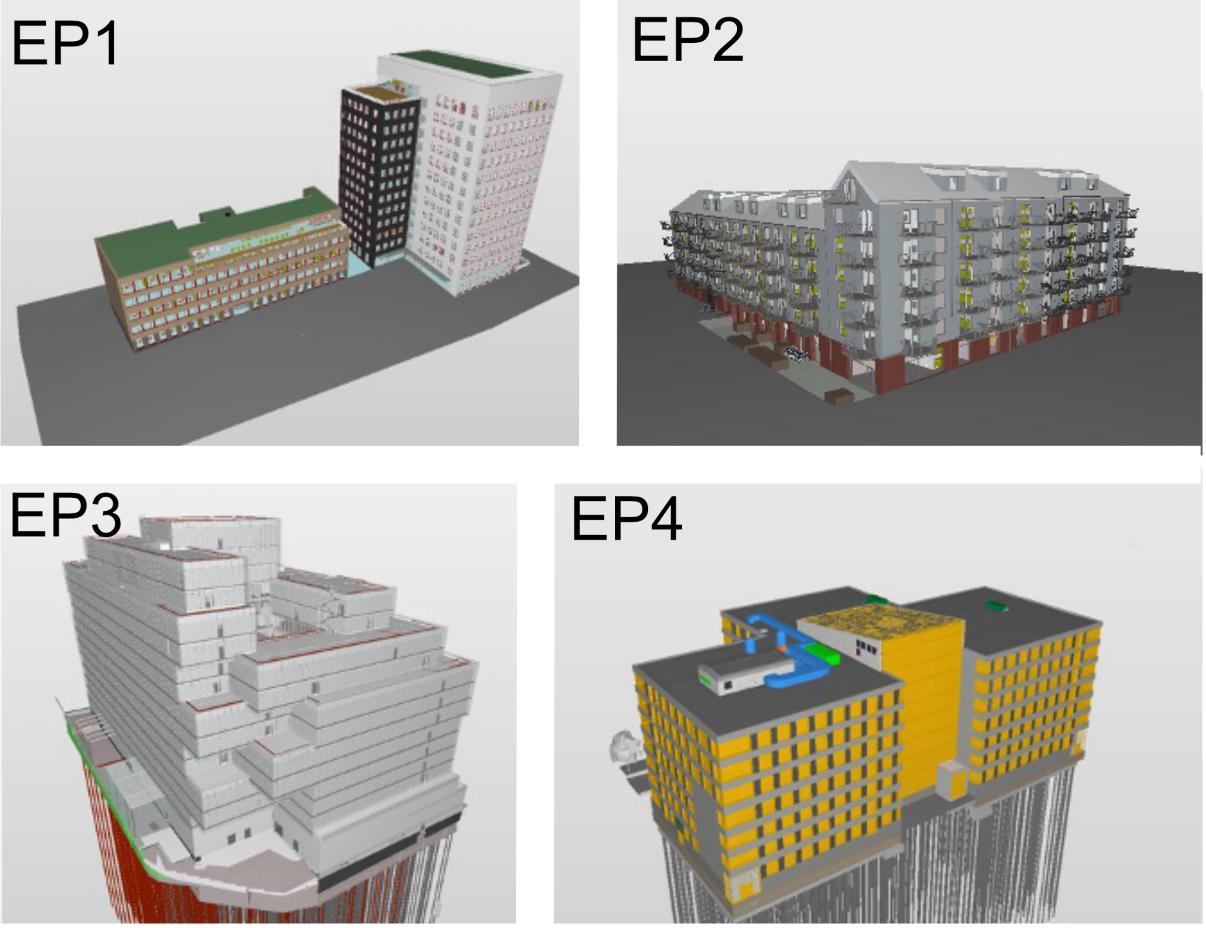


Figure 3.3: The different projects EP1, an office complex of ca 15 000 m^2, EP2, an apartment blocks at ca 7000 m^2, EP3, an office and hotel combo of ca 60 000 m^2 and lastly, EP4, a office building of ca 20 000 m^2.

The evaluations used four different projects as the basis for the evaluations. Figure 3.3 shows the four projects with some notable short data about the projects. The projects in the table are numbered EP1-EP4, short for evaluation project. The reason for using different projects was partly due to the development of the available building models and partly from the participants in the evaluations. During evaluations using CFGs, the aim was to use models and a setting taken from a project the participants worked in.

EP1 was the first project used in the evaluations, and it was classified as a flagship BIM project in 2014. The building model was well developed, with classifications and other production-related information in the model. The switch to EP2 was in preparation for a CFG evaluation that did not happen, but the development of the model was slightly better than EP1, so this model was used for evaluations no #3-#13.

In evaluation #14, a CFG, a new office project, was selected. Once again, this switch was made to use projects the participants participated in daily work to focus on the planning process and the VPP-system. For a more detailed description of the VPP-system see Chapter 5. This switch enabled the researchers to evaluate a planning and scheduling session similar to the original process but enhanced with the developed artefact. The model this time was also more detailed than previous models used. Lastly, in evaluation #15, a new model was selected again to use the participants' current project. This office building, EP4, was the most detailed building model used to date, with highly detailed information aimed at the construction production process.

The time constraints of the evaluations meant that the evaluations were limited to a subset of the CPP process using the VPP-system, only going through one zone of the project being planned. The size and location of the zones were taken from the CPP scheduling sessions, enabling evaluations to follow the original sessions as closely as possible and focus on the artefact's effects on the planning process.

The selection of the evaluation participants has been made according to role and experience. Access to middle management positions and specialists has been easier than actual on-site management and workers, which is a research limitation. A detailed account of this can be found in Paper IV.

3.2. Research method and design reflection

The selection of DSR as an overarching research paradigm has helped keep eyes on the planning process and the social interaction in the collaborative planning approach, balancing the influence of the technological view. Furthermore, engaging in the observations and the initial collaborative planning and scheduling workshops helped form an understanding of the issues prevalent in the workshops. However, this immersion should be balanced with the risk of becoming biased toward certain solutions and may contribute to limitations in the research.

Approaching DSR as the primary researcher with control over observations, design, development and evaluations has meant that I, as a researcher, had complete control over the artefact and the development and could separate technical issues with the artefact from potential process issues during evaluations. To have control over the development also meant that alternative agendas that the developers or stakeholders might have could be mitigated and managed. While the researcher has been the lone developer of the VPP-system, this has also brought a thorough understanding of the system and what is possible to achieve during the development and evolution of the artefact.

A downside could be that the DSR approach, combined with the size of applicable projects used as examples, probably contributed to the fact that a full-scale project evaluation in an actual ongoing project never occurred. The size of the projects selected needed to be big enough to have sufficiently developed building models, especially during the first few evaluations where building models were not as common as later projects. Thus, the building models limited the possibilities of evaluations in actual projects and planning sessions. Such tests were deemed needed to contribute to the project at hand and not duplicate planning work already done to be acceptable to the project team.

3.3. Ethical Considerations, Trustworthiness and Quality of Data

The research ethics for all the interviews, observations and evaluations in this study has been conducted with informed consent. The researcher has practised openness during the data collection by explaining the usage and purpose of the collection before collecting data. All participants have been anonymised where possible, reducing gathered personal information to role and experience, where pictures have been used, participants are anonymised, protecting anonymity and confidentiality. As the research has focused on the collaborative process and how it can be supported by ICT, the participants' role has been essential.

From an ethics point of view, the research results generally strive to keep the participants' roles. As observed in the current collaborative planning and scheduling practice, middle management roles such as site management and specialist planners take a step back and act more as facilitators than a principal powerhouse. Thus this research entails a risk to further alter the traditional role of the site manager and specialist planner by promoting the decision power of supervisors, forepersons and subcontractors, concerning the planning and scheduling. However, as stated earlier, this is already in line with initiatives taken to promote the collaborative planning and scheduling process in general and should, as such, not pose a particular risk.

The DSR approach has also kept the focus on the people in the process and could thus be argued to help keep the participants and practitioners needs in focus. The use of actual projects as examples could be argued to increase the trustworthiness of the results since the quality of the data resulting from evaluations thus is closer to actual planning sessions on-site. Using actual projects as data without altering or adding information other than breaking models into zones as stipulated by the original project also kept results potentially closer to actual planning sessions.

There is little risk for ethical dilemma from the sponsorship of the research, since the research is fully funded by the Swedish construction industry's development fund, even though one of the big contractors in Sweden was one of the co-applicants in the research project, all interested contractors have been welcome to participate and take part of the outcomes of the research. The research projects reference group included the five most prominent contractors in Scandinavia, and planners from all contractors participated during the project, thus ensuring a broad picture of the insights around similar planning methods and approaches in these companies during the evaluations.

With regards to the selection of participants could somewhat be argued to be some limitations. Partly the selection has been according to availability; for example, a site manager ensured that the subcontractors took time for the initial interviews, partly through interest, as the case was with the evaluations. Sine evaluators were not picked randomly, and the evaluators knew about the evaluation and goals of the evaluations beforehand, a certain bias should be expected. However, since different groups of evaluators were used, the potential bias could be argued to lessen; this also brought some interesting insights, as can be seen in Chapter 6.

4. Summary of the papers

This chapter summarises the result of the four appended papers, one conference article, two journal articles and one submitted journal paper in the review process.

4.1. Paper I - An empowered collaborative planning method in a Swedish construction company - A case study

Viklund Tallgren, M., Roupé, M. and Johansson, M. (2015), in 31st annual ARCOM Conference. Association of Researchers in Construction Management, pp. 793–802.

4.1.1. Purpose

The purpose of the first paper is to set the stage for the DSR project. Thus, the first paper focuses on RQ 1, and touches lightly on the design of the artefact RQ 2. The observed collaborative planning method is positioned compared to other planning methods in construction. The planning method is studied in the field in an ongoing project. The paper aims to describe the planning method and study the interaction with the information, and between the participants to position the method with regards to BIM.

4.1.2. Method

The paper combines a single case-study approach, where observations of three full-day sessions are the primary source of data collection, with a literature review and seven interviews as background material. The initial work consisted of mapping current planning methods and streams of planning. The interviews served to identify the kind of information that the sub-contractors used in their planning. Three observations in collaborative planning sessions were conducted in the case study project, where the primary author in the last two sessions participated as a model-navigator. Observations were recorded in field notes after the sessions. Together with the transcribed interviews, these notes were then coded through open coding, generating keywords that were grouped into category themes.

4.1.3. Findings

The interviews also showed that the workers knew of the building models but had little practical experience of them. Many of the interviewees saw possibilities for BIM to contribute to a better planning process. The use of forepersons from the sub-contractors is an empowerment move (cf. Dvir et al., 2003; Faniran et al., 1994; Laufer, 1992; Dainty et al., 2002), and comparable with the last planner approach.

The low-tech approach with sticky notes effectively involves the participants but creates long lead times from draft to digitalised schedule. The observations show that the BIM use shows potential, but there were barriers to the use, such as workers could not use the model themselves. Few tools for collaborative co-location planning exist, and existing tools are aimed at more traditional non-collaborative methods and specialist planners.

4.1.4. Contributions

To summarise; Two main contributions were identified; number one was that the planning method was related to several collaborative planning methods and had similar benefits. The second finding was that the large amount of information available in the project also used by respective disciplines made it hard for the disciplines to find the correct information at the right time, thus hinting at possible enhancements.

4.2. Paper II - BIM-tool development enhancing collaborative scheduling for pre-construction

Viklund Tallgren, Mikael; Roupé, Mattias; Johansson, Mikael and Bosch-Sijtsema, Petra, in International Journal of Information Technology in Construction, 2020

4.2.1. Purpose

The second paper aims to outline the requirements for the artefact and how the design was developed. The paper focuses on the requirements that are the basis for developing the enhanced collaborative planning and scheduling system and thus primarily addresses RQ 2.

4.2.2. Method

The paper extends the observations from Paper I with additional participant observations to collect insights of practice as-is, this time with another project, further saturating the insights of the collaborative planning and scheduling method in use. The data from the interviews in Paper I was added, and themes were identified and recorded for later use during requirement identification. The design was then evaluated in a series of six evaluations. The evaluations were done in a lab setting but using real-life projects as evaluation objects. The projects were one five-storey apartment building. The first two evaluations were made during the design loops to get to a stage where the prototype represented the majority of functions used in the original workshop. The participants were selected from the research team, with two researchers and an expert planner participating. The data was gathered through observations as well as a sound recording of the workshop.

4.2.3. Findings

As seen from the literature, the collaborative and empowering approach supports and pushes in a positive direction for the projects. An example of this is the Last Planner System (LPS); a downside with LPS is the need to change planning processes to conform to their approach of production control. This need to change processes is generally viewed as a barrier for implementation due to the site managements limited time to learn new processes and change ways of working (Christiansen, 2012; AlNasseri and Aulin, 2015). Also seen from literature and observations is that BIM-use is most common amongst site management, where BIM models are used, they are seldom referenced by workers directly, but often through site management or supervisors (cf. van Berlo et al., 2015).

The implemented Virtual Production Planning (VPP) system shows that it is possible to create a more collaborative planning system, using collaboration criteria from observations of the actual process and the collaborative virtual environment literature to ensure support for many types of collaboration. The evaluations point toward more focused workshops and time reductions in digitalising the schedule and time gains from draft schedule to finalised production schedule.

4.2.4. Contributions

There is a lack of adoption of new construction management tools, often related to a lack of time and willingness to learn new processes these new tools bring. The evaluations of the developed VPP-system shows support for collaborative planning methods in general, showing improvements in how participants can engage and interact with the model and schedule. The VPP-system promotes involvement and enables sharing of knowledge, and it also shows the potential to reduce the time from draft schedule to finalised production schedule through the increased possibilities to review the sequenced schedule during creation.

4.3. Paper III - 4D modelling using virtual collaborative planning and scheduling

Viklund Tallgren, Mikael; Roupé, Mattias; Johansson, Mikael, in International Journal of Information Technology in Construction, 2021

4.3.1. Purpose

The third papers primary purpose was to position the developed artefact with relation to other 4D software. The paper builds in the evaluations of Paper II and extends these initial six evaluations to fifteen. The paper's main aim is to compare existing 4D modelling approaches, thus furthering the relation to the knowledge base, thus touching upon RQ 2 as well as RQ 3.

4.3.2. Method

This paper builds on the interviews, literature reviews and observations from previous papers. Three additional observations of the collaborative planning and scheduling method are performed to study the use in various projects. Eight evaluations were to test the process and evaluate against best practice, with planners and middle managers from the five major construction contractors in Scandinavia.

The paper also uses the literature review, observation and an interview with a project planner to analyse and model the planning processes described in the paper with a process modelling approach. The processes are visualised through the business process modelling notation as a reproducible way to communicate process flows (Borrmann et al., 2018, ch. 4).

4.3.3. Findings

The paper describes the general 4D planning process, showing how it extends the general planning process and links the previous process's schedule with a model to create the 4D model. The literature argues that collaboration in available scheduling tools is absent, especially concerning 4D (Campagna-Wilson and Boton, 2020). The paper builds on this, extends the discussion about collaborative and involved approaches, and shows the possibility of utilising immersive VR in the scheduling process, drawing on evaluations and experiences from immersive VR in design review and constructability sessions. The immersive capabilities are extended to other platforms through the VPP-system API. Initial tests with immersive interaction and planning in VR show potential to further user communication. Users can interact in the model on a real-world scale, querying information and taking measurements.

4.3.4. Contributions

The paper contributes through the instantiation of the collaborative planning and scheduling method in the VPP-system. The evaluations show that VR and HMDs facilitate a better understanding of the project and the schedule review process. Thus, the use of 4D planning and modelling increases the worker- and subcontractor- engagement. The paper reinforces previous findings that VR supports better sequence planning and constructability analysis.

The integrated 4D modelling and scheduling approach makes it possible to make changes in the 4D schedule in the web-based scheduling interface and have the changes instantly updated in VR. Thus, the paper argues that 4D is not static, and the use of the VPP-system promotes social co-creation in different spaces and can help better understand different points of view and the connection of different subtasks between various subcontractors.

4.4. Paper IV - A BIM-based collaborative production planning system: Design, development, and evaluation

Viklund Tallgren, Mikael; Roupé, Mattias; Johansson, Mikael,

Submitted to *Journal of Construction Engineering and Management*

4.4.1. Purpose

This paper is thought of as the capstone of the DSR research project. It presents the final prototype of the VPP-system and focuses on the fifteen evaluations of the prototypes leading to the final prototype. Thus, the fourth paper touches lightly on the design of the artefact RQ 2. This paper also focuses on the contributions through RQ 3.

4.4.2. Method

This paper builds on the prior literature reviews, interviews, observations, and evaluations gathered together; in this paper, all the fifteen evaluations are detailed, with projects used, participant selection for the evaluations, durations, and how data was collected, also seen in Chapeter 3 of this thesis. These latter evaluations utilised mostly project planners and middle managers for the evaluations. The last two evaluations were the closest to production, with site managers and BIM specialists from production participating in the evaluations.

4.4.3. Findings

The literature shows research focus on new technologies and new process rather than developing and supporting existing processes. Thus, the fourth paper addressed these shortcomings by describing findings from the fifteen evaluations of the tool, focusing primarily on the latter set of evaluations which included site managers and BIM specialists, intended users of the system. The evaluations showed general support for the VPP-system, with participants commending its usefulness. The evaluations showed that participants better oriented themselves in the VPP-system and that discussion in the sequencing part of the workshop became more focused than before. The possibility of instantly reviewing the scheduled sequence with the 4D model improves the traditional unenhanced method.

The evaluators also commented on the low trust in currently available building models, highlighting the need for models better aligned to the production. Amongst the evaluators, a clear division between middle managers and more site management-focused participants appeared. The closer the participant was to the construction site, the more focus was on processes, and the general utility of the VPP-system and the less focus were on the presentation of schedules and planning theory and existing scheduling systems.

Several evaluations were conducted with one or several evaluators participating remotely, validating the possibility of conducting workshops effectively with remote participants. While possible, it was concluded that on-site participation was preferable but not necessary. It was also seen that the VPP-system engaged participants more than in the original workshops, which helped build a better understanding of the project.

4.4.4. Contributions

From the evaluations, it was clear that the VPP-system was judged more disruptive for middle management, indicating that their fixed routines and tools provided a barrier to implementation, which was also expected since the VPP-system was developed aim at use on-site in production. The major contributions are as follows:

1. The gap of collaborative planning systems are addressed through the implemented VPP-system.
2. The VPP-system is more disruptive for middle managers than for site management.
3. There is a need for BIM models to align information to production needs.
4. The use of the VPP-system reduces the cognitive load in scheduling and increases focus on the planning task.
5. Schedules can be reviewed instantly without translation from physical draft to digital, reducing turnaround time from draft to final schedule.
6. The VPP-system engages the participants, making participants more active and thus increasing project understanding and ownership.
7. The VPP-system reduces the need for co-location, even though it still is beneficial.

Thus, the paper addresses RQ 3, contributing both to the body of knowledge of collaborative IT systems in construction and how these systems could support communication and collaborative processes in a social context and contribute to practice with a system enabling interactive 4D modelling and scheduling.

5. The Virtual Production Planning system

This chapter gives an overview of the developed Virtual Production Planning system.

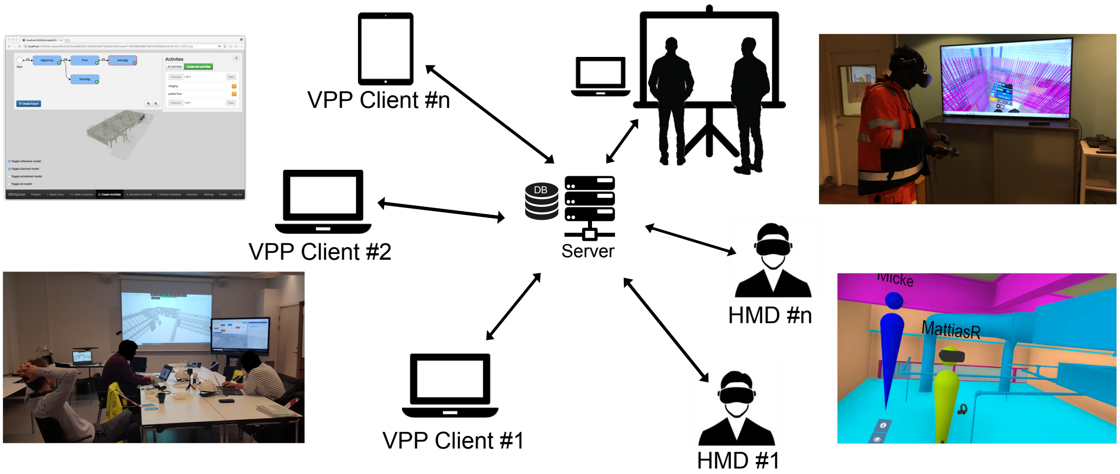


Figure 5.1: overview of the setup of the VPP-system and clients.

A big contribution of this thesis is the development and evaluation of the Virtual Production Planning (VPP), system, shortened to the VPP-system hereafter. The VPP-system enables collaborative planning and scheduling using building models as the basis for planning. The VPP-system can be described as a backend with a web server serving an Application Program Interface (API) connected to a database. The primary frontend is a web application also served by the webserver, but the API enables integration and interaction with other applications such as desktop applications for non-immersive VR or head-mounted displays with immersive VR. A schematic figure of this can be seen in Figure 5.1. The implementation of the VPP-system follows the Collaborative Production Planning (CPP) process described in Paper I, Paper II and Paper IV, and shown in Figure 5.2.

The three main stages of interaction are:

1. Preparation and review of the project and location,
2. Individual planning of location,
3. Collaborative planning and review of the location.

These three stages map to corresponding stages in the CPP-process and is an iterative process; columns symbolise these in Figure 5.2. All these stages take part inside the VPP-system. The first stage, preparation, is to get the building models into the system; this stage has, during the development, also incorporated the definition of work packages as zone or parts of the model.

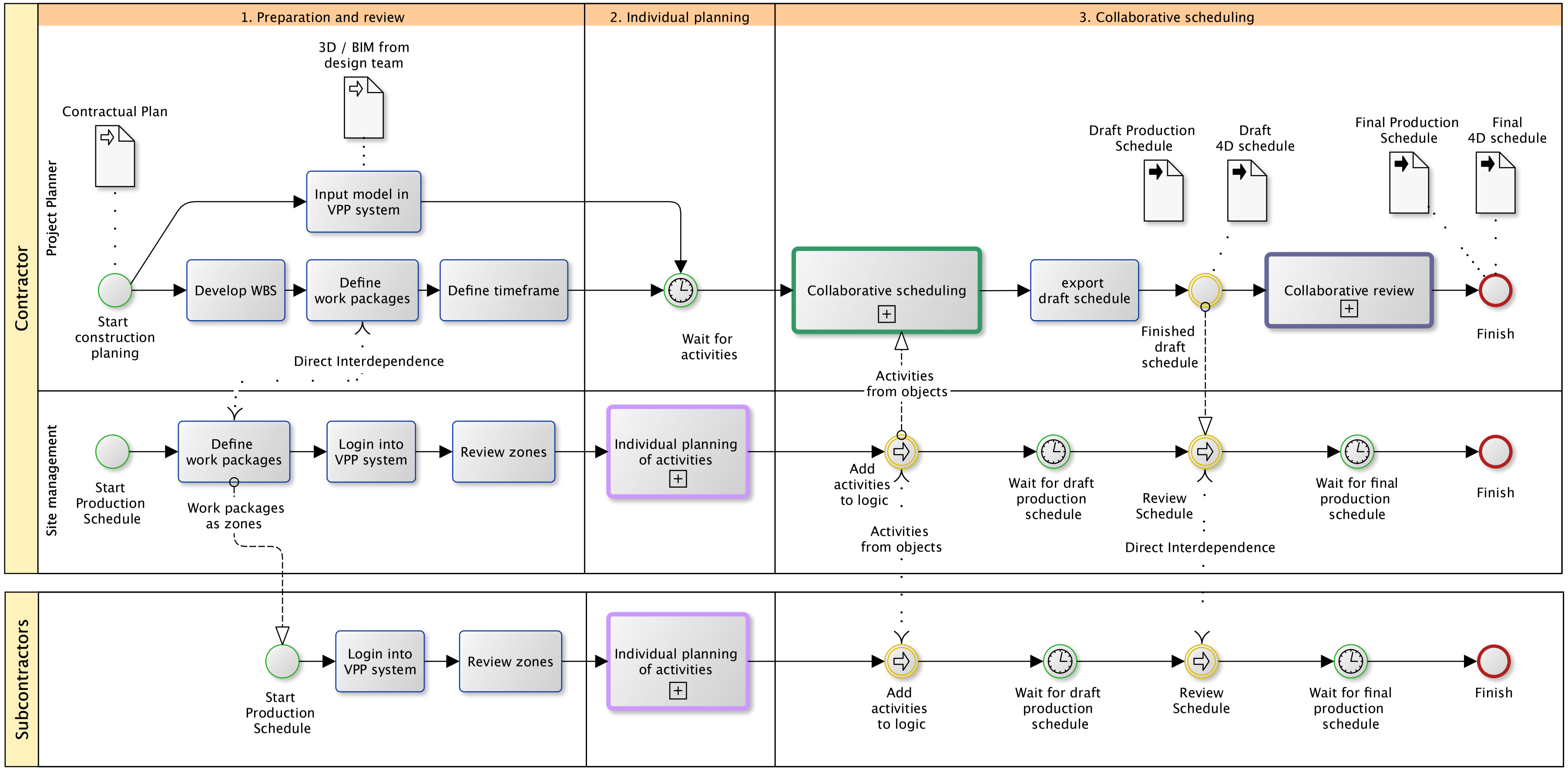
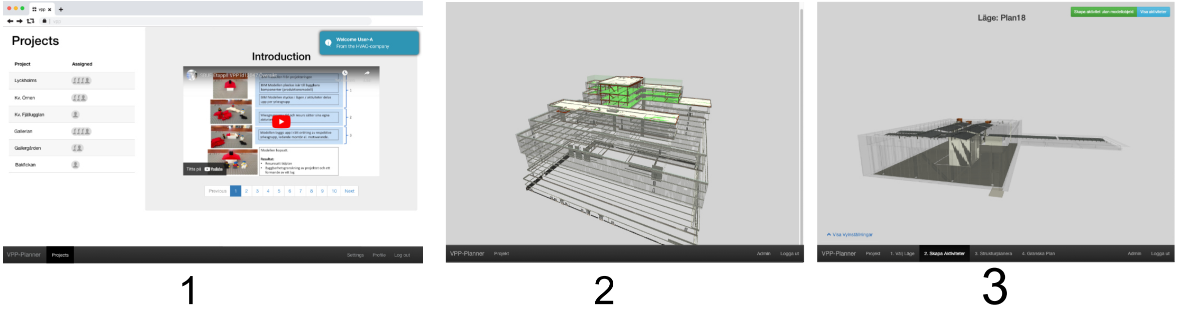


Figure 5.2: The process modeling of the VPP-system.

In most cases, this meant using the original building models, IFC files or Revit files, and loading them into Revit, using a plugin in Revit to export geometry and metadata packaged for the webserver. The original files have been used ”as-is”, and each discipline was supplied from the original project as separate files. This structure was kept in the VPP-system and was essential to the separation of concerns between different disciplines.

As each discipline logs into the system, assigned projects are displayed, and the user can select the current project to work with. By selecting the project, as seen in 1 in the left part of Figure 5.3, a lightweight 3D representation of the project is presented, showing the different zones and possibly subzones of the project. The user then navigates by pointing and clicking on the specific zone/subzone, as seen in 2 in the middle of Figure 5.3, to load the building model for that zone. When the zone is selected, as seen in 3 in the right part of Figure 5.3, the users can proceed with the review of the project in that zone, this prepatory work enables the users to get to know the project at hand and identify challanges pertaining to thier discipline in each zone.



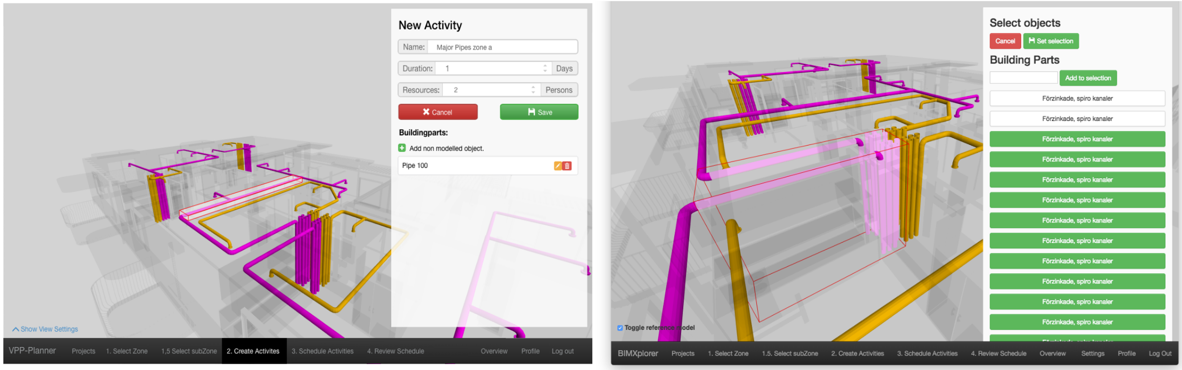
Welcome User-A
From the HVAC-company

Project	Assigned
Lyckholms	
Kv. Örnen	
Kv. Fjällugglan	
Gallerian	
Gallergården	
Bakfickan	

Figure 5.3: 1. Selection of proejct view, 2. Select zone or subzone, 3 Selected zone.

The second stage is individual planning; this corresponds to the creation of sticky notes with activities in the CPP process. Here the participants interact with the model and pick or filter visible objects, making up the activities, as seen in Figure 5.4. The activities are given resources and durations, just like the sticky notes. All disciplines do this individual work. The disciplines get a visual check that a zone is planned since all building model objects should be part of activities. When the view is emptied of objects, all work represented by objects are planned, although work such as painting, or smaller tasks not having modelled representations could still be missing. Up until now, the user has worked in the specific zone in a ”creation/review” view of the model. Once all disciplines have finished planning their activities, which could be work done beforehand, the collaborative scheduling stage begins, all the participants gather and switch to the scheduling view.

In this stage, the users switch to a view where they have a list of their activities on the right side of their screen, see in the left part of Figure 5.5. In the upper left of their screen, the users see the full schedule for the zone; it grows as the disciplines add activities to the schedule. The schedule and activities are collectively discussed, and activities are placed by each discipline as agreed during the discussion. The schedule is updated simultaneously in each participants browser, enabling



Name: Major Pipes zone a

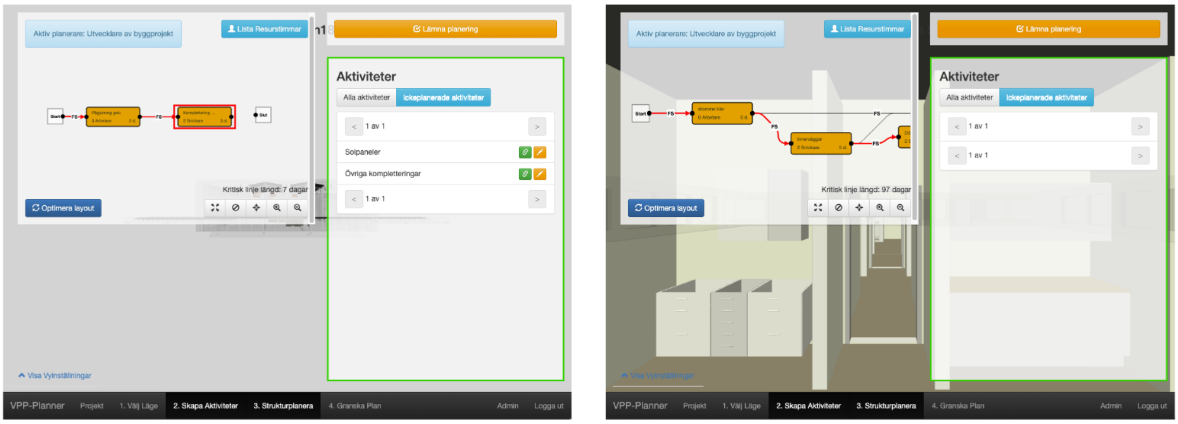
Duration: 1 Days

Resources: 2 Persons

Pipe 100

Figure 5.4: The user Part selection (left) and multipart filtering (right).

users to see changes as they happen. The schedule calculates the critical path and duration for the zone in as the schedule is created, as seen in the right part of Figure 5.5.



Kritisk linje längd: 7 dagar

Kritisk linje längd: 97 dagar

Figure 5.5: The Schedule sequencing view (left) and schedule review view (right).

At any time during the collaborative scheduling, the participants can switch to a schedule review mode, where the schedule can be reviewed if properly connected. The schedule review mode allows the users to step chronologically through the schedule. When a user slides the timeline forward or backwards, it causes the activities with corresponding objects to update colouring according to their status in the schedule at the given date, as seen in Figure 5.6. Planned but not yet started objects are transparent, objects being built is green, and finished objects obtain their original colour or material. This enables the users to spot errors in the schdeule logic early.

As described in Paper I and II, these three stages are repeated for each unique location. A location could be a level or a subdivision like a zone or even a room in a complex project.

In Figure 5.7 selected views from the VPP-system and stages are illustrated.

The second stage, the middle part of Figure 5.7, shows the user planning activities or activities for the schedule. As in the CPP process, each activity consists of a name, duration, and resources

Figure 5.6: Review of the schedule, active tasks coulured green.

allocated, but in the VPP-system, parts from the building model are directly selected, and data from the parts is available when the activities are created.

In the scheduling view, each user sees two larger panes. The first one, in the upper left corner, is the schedule that is being developed. The schedule view is identical for all users, and every interaction is replicated between the users. On the right side of the screen, the second pane lists all activities for the discipline and zone. The collaborative planning session continues as in the CPP process, where the participants discuss who is going next, gradually discussing and agreeing on the sequence of activities. In the screen's background, the building model's zone gradually becomes visible again, as the sequencing of activities is happening. The list of activities on the right-hand side of the screen is reduced as activities are scheduled.

The users can switch to the 4D visualisation mode at any point, where the users can use a sliding timescale to review the schedule at any given point of the sequence. In the lower right part of Figure 5.7, a user using an Head-mounted display (HMD) is reviewing a sequence on a scale of 1-1, as if virtually building. The HMD VR interface listens to changes in the time slider and updates accordingly.

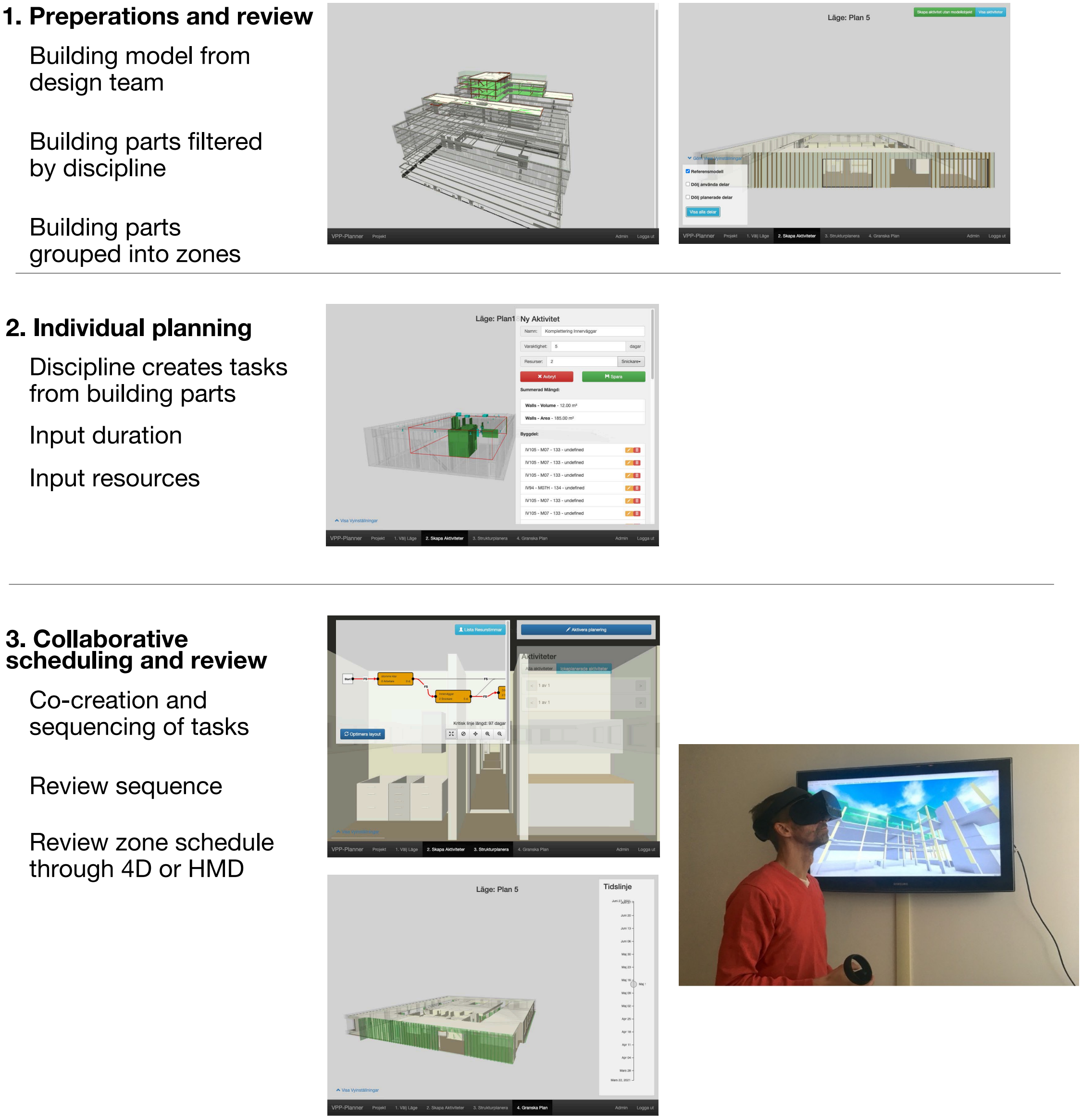


Figure 5.7: Selected views from the VPP-system.

6. Analysis and Discussion

This chapter uses the research questions as a general outline but focuses on the DSR process as a basis for the analysis and discussion. It starts with an analysis and discussion of the traditional and collaborative planning processes in the thesis. Then continues with analysing and discussing the requirements and the development. The analysis and discussion then end with the instantiation of the collaborative planning process in the form of the VPP-system and analyses and discusses its evaluation and findings.

The focus of this thesis has been twofold, firstly, the observation and documentation of a collaborative preproduction planning and scheduling process CPP, and secondly, the design, development and evaluation of the Virtual Production Planning (VPP)-system; see the previous chapter for a description. In essence, the VPP-system is an instantiation of the CPP process. In this context, it is crucial to understand the environment and the knowledge base of the related research areas. The following sections use the research questions to thematise the analysis and discussion of the approach, the design, development and the evaluation, starting from RQ 1 - *How is a collaborative planning process performed in construction production, and especially in a Scandinavian context?*

6.1. The use of collaborative planning and scheduling in construction production

While collaboration and involvement are encouraged by literature (cf. Bhatla and Leite, 2012; Crowther and Ajayi, 2019), it is mainly promoted through lean initiatives such as the Last Planner System. In Sweden, a collaborative planning process for traditional scheduling methods such as the prevailing Critical Path Method (CPM) was developed during the 1980s but did not seem to have gained a foothold (cf. Söderberg, 2006).

Furthermore, literature shows that this collaborative planning process called Integrated Planning (IP), developed along with the lean initiatives and exist in parallel with these nowadays (Söderberg, 2006). Variants of this process are applied around Scandinavia in the larger construction companies, as seen from the evaluations in Paper III and IV. These implementations is in line with the discussion around communication, empowerment and involvement seen in research (cf. Dainty et al., 2002; Dvir et al., 2003; Dainty et al., 2006; Simonsen, 2007; Friblick and Olsson, 2009; Winch and Kelsey, 2005). Furthermore, the observations show that the IP-variants used in the different construction companies have originated from perceived demand from the onsite management. As discussed in research with regards to the implementation of Lean methods, this approach poses the dangers of a lack of standardised implementation and should be balanced with some top-down anchoring as well to ensure a standardised implementation (cf. Elfving, 2021). The IP approach today originates from site management and project planners. This bottom-up anchoring makes the use of the process easier to motivate and engage stakeholders since the site management can see and communicate the value of the process, as seen with the subcontractors in the observations in Paper I and II.

The observations in Paper I, II and III show an acceptance of involvement and collaboration in general production planning in Sweden. Discussions during and after the observations with participants of the scheduling sessions showed that the participants appreciated the collaborative approach but admitted that they were a bit sceptical initially, wondering why they should spend several days in workshops planning and scheduling together. However, their conclusions during discussions and after observations were that the engagement and involvement increased their knowledge of the project and helped reduce problems with the schedule later in the production.This engagement improved their motivation to participate and decreased their reluctance. Through comparisons of the observations from Paper I, II and III and the evaluations support these statements.

During the evaluations in Paper III and IV, discussions with planners from the five different construction companies explained that they used similar collaborative techniques for production planning, at least in larger projects. However, the planners also admitted that it was hard to get the right people involved early due to lack of time and partly due to subcontractors and onsite management not being selected or hired when the production planning was supposed to occur.

These observations show that while collaborative approaches are used, there is still potential to make more planning collaborative in construction and that the industry could benefit from it. The literature's recommendation to promote engagement and collaboration still stands (Dainty et al., 2006; Chowdhury et al., 2020), and even with the limited set of observations in this research, the industry in Sweden seems to be moving in that direction, albeit slowly. The research argues that new processes and approaches may be hindered due to the lack of time to learn these processes. This lack of time means site management falls back into tried and tested processes that are well known to them (Christiansen, 2012; AlNasseri and Aulin, 2015). This is also supported through comments from a site manager in the later evaluations of the VPP-system, see Paper IV.The thesis highlights the need to identify collaborative planning practices and thus identify the CPP process and understand how the CPP process is practised.

This brings the question of the characteristics and key process elements that make up collaborative planning and scheduling, especially the CPP process studied here. While this discussion touches upon RQ 1, the following section delves deeper into the discussion of what constitutes collaborative planning in construction.

6.2. Characteristics and key process elements in collaborative planning

Construction projects often take on a project-oriented organisation, with each project more or less acting as a separate company, with little overlap between project organisations. This compartmentalisation produces a constant need for team building. Project organisations start more or less from scratch in each project (cf. Gamil and Rahman, 2017), and thus forming communication channels and increase trust and respect in the team, the team building, put a strain on the onsite management. The CPP process described in this thesis relies on the stakeholders performing the work to plan and schedule actively. The planning is thus moved from the planner to the subcontractors that are selected to perform the work. This is similar to how the literature describes the last planner approach and its form of collaborative planning (cf. Ballard and Howell, 2003). The observations of the CPP sessions show how the planning work is moved from being traditionally done by the planner or site manager (cf. Winch and Kelsey, 2005; Christiansen, 2012), to being done collaboratively with each subcontractor planning their part. The observations show that by doing the schedule collaboratively, the different stakeholders get to know each other, discuss and schedule the sequence together, and understand how their work affects each other, arguing this to be a sign of countering the fragmentation mentioned in the literature.

The observations show that this is where the CPP process differs from LPS; while LPS is an entire management approach, the CPP process is comparable with the stage of phase planning in the LPS system (Ballard and Howell, 2003). From Paper I, II and III observations, the CPP process has roughly the same detail-level as phase planning in the LPS system, and it also engages the subcontractors in the planning work. However, the main difference is that it does not use the pull-planning approach stipulated in LPS but instead starts with a discussion of what work should be performed first, giving the initial activity and then through the collective discussion led by the project planner. The participants decide the following activities, focusing on what activities are enabled by the current activity; this could be described as a combined push-pull type of scheduling since the schedule is pushed forward, while the subsequent activities are prodded and pulled until the following activities are identified and sequenced. Here the CPP process thus deviates from LPS, which starts with the finish date and activities are added from the end, only pulling activities that enable the current activity until a starting point is found. The push planning of activities is the prevalent technique and perhaps the most intuitive as well. While effective in identifying only the activities needed to be finished to start the activity doing the ”pulling”, the pull planning approach requires the participants to approach the planning in a new way.

While the CPP process is seemingly simple, the four sets of project observations were used to validate the initial observations and the requirements developed from these. The use of multiple projects also allowed for cross-referencing the CPP process between slightly different projects and organisations, developing and confirming requirements between design cycles. This approach helped document the CPP process and validate the approach between different projects and participants, which gave a saturation of the observations.

The characteristics of the CPP process found from the observations were compared and contrasted with the literature (Fischer et al., 2005; Snowdon et al., 1998). The CPP process manifests many of the properties seen in the literature concerning collaborative virtual environments, focusing on the collaborative aspects. The emphasis of the CPP-process is, for example, to *create awareness of each other's work, build on the work of others* and *the shared context to enable shared understanding* as presented in Paper-II.

During the observations, it became apparent that the CPP process helped bring the team together and increase the understanding of the project while reducing guesswork in the scheduling. In the observations in Paper I, II and the process modelling in Paper III, it can be seen how the collaborative planning process builds upon the open and free communication between participants as stipulated by the literature (cf. Snowdon et al., 1998). The planning session setting creates a setting that promotes communication, where the planner acts as a facilitator, ensuring that all disciplines contribute. Thus, it could be argued that the planner goes from enforcing a schedule, as seen in many traditional project settings, towards creating an open information exchange regarding the planning and scheduling, as asked for in the literature about communication (Dainty et al., 2006).

In general, the observations show that the CPP process builds the team and trust, two components lacking in projects as argued by Arditi et al. (2017). This increase in team trust and team identity is also hinted at in Paper I, where participants unsolicited commented on the increased cooperation and likelihood that they would pick up the phone and consult each other if questions arose. Furthermore, the observations also show that engaging the right person at the right time reduces the guesswork of the schedule, as suggested in literature (cf. Dvir et al., 2003), an argument also exemplified in the last planner approach to planning. During the observations, the interaction between the participants was high, especially during the sequencing of the activities, to the extent that the lead-planner and facilitator of the workshop had to remind the group that it was one meeting and not several small meetings. However, as a positive side note, the direct interaction meant that questions and issues often were solved on the spot.

It should also be noted that parts of the CPP process produced unnecessary waste in terms of waiting and information gathering visible. While the low tech approach of sticky notes is accessible and easy to use, the resulting schedule still needs to be manually put into scheduling software for the team to review and get feedback on the created schedule. This waiting for manual input could probably be somewhat alleviated by enforcing a timescale on the paper the schedule is planned. However, interviews with the planner that used the CPP process showed that the approach to plan and schedule without regard to contractual milestones and dates initially focuses the work on the sequence and logic. By breaking down the project into manageable locations and focusing purely on the schedule logic and sequence, the complexity of the planning problem is reduced. By reducing the complexity of the planning problem, cognitive load is also reduced, and focus can be spent on the planning and scheduling problem instead, thus resulting in a draft schedule faster. Once this draft schedule is transformed to a digitised ideal schedule, the review and alterations can be done. This seamless review and alteration process addresses similar issues found missing in the literature, (Boton, 2018). Thus, this constitutes a contribution to the planning and scheduling literature.

As noted in Paper I, II and III, even with the CPP process, long lead times between the collaboratively developed draft schedule and the digitised draft schedule was expected, indicating room for improvement as seen in Paper III. In the CPP process, the digitisation of the schedule takes the specialist planner 1-2 weeks, depending on the size of the project and the number of other projects the planner is responsible for, risking the participants to lose the train of thought, going back and forth between projects. Improving the lead times would mean that the participant can do the review closer to the draft, connecting the process.

6.3. ICT support of collaborative planning and scheduling

This brings the question of ICT support in the collaborative planning and scheduling process. Research question RQ 2 - *In what ways can ICT for visualisation with building models support collaborative planning and scheduling?* questions the situation of ICT support for collaborative planning.

The DSR approach taken in this thesis exemplifies the more holistic approach advocated by Fischer et al. (2005); Zhou et al. (2014); Sackey et al. (2015) for the development of collaborative tools from the users' needs and perspective. The CVE literature supplies core requirements for collaborative virtual environments, which, combined with the CPP process observations, enables the development of a digitalised collaborative scheduling system. The nine core requirements (2.2.2), identified in CVE literature (cf. Fischer et al., 2005; Snowdon et al., 1998), coincides with many of the characteristics that collaborative planning expresses studied in the CPP process.

Table 6.1 shows the main requirements and how they were addressed during the development of the VPP-system.

While Table 6.1 shows the four general requirements and how these are addressed, as described in Paper II, the requirements are geared towards the specific properties and elements identified during the observations of the CPP process. A broader set of requirements and principles were used but could be argued to be expected for all types of planning systems and thus does not add to the specific discussion about collaborative planning systems.

Requirement	**How Requirements are addressed in the VPP-system**
1. Help users gain overview of project and disciplines	- Break down model into smaller zones - Navigation to specific zone - Limit visible information - Possibility to show / hide other disciplines in specific zone - Possibility to interact with model in zone - Creation of activities stored in database - Model distributed from server
2. Support individual and group work	- Interactions with specific zone is individual and customized to user - Create activities from filtered zone view - Share work within a discipline - Co-creation of schedule when sequencing activities - Distance participation possible
3. Support information gathering while creating activities	- BIM model provides information - Users can specify information shown by model - Information is hidden until hoover over element or click on element - Specified information acts as input in the activity - Information is summarized as preliminary take-off quantities - Planned parts are hidden until scheduling starts or user override - Gives visual feedback of what is planned - Users able to interact and discuss around model
4. Support collaborative creation of the schedule	- Every user can see and interact with the full schedule - Several users can interact with the schedule simultaneously - Possibility to show / hide other disciplines in specific zone - Visual feedback from the model on what is scheduled

Table 6.1: Requirements and how they were addressed in the developed VPP-system, adapted from Paper II.

For example, knowledge sharing and creating awareness of each other's work are emphasised through the collaborative process and the discussion of the scheduling sequence. The participants create understanding and awareness of their respective activities through the discussions and create a shared understanding, highlighting the negotiation and communication aspects in the CVE literature (ibid.), and is mapped to the shared context and space in which the CPP process is conducted.

The shared context and multiple viewpoints stressed by the CVE literature (ibid.), further connects the collaborative scheduling process of CPP with CVE. From the observations, it was apparent that multiple viewpoints were often required to understand the planning and scheduling challenges better. In the later observations, OP4 and OP5, the projects had a more mature building model integration than seen in the research's early projects (OP1, OP2 and OP3). However, ICT support in the form of BIM viewers was still sparingly used. As seen in all observations, the use of the BIM viewers was limited, somewhat hindered by reluctance and lack of knowledge of how to use Solibri amongst the subcontractors.

Furthermore, analysing how the building models were used in the CPP process, the first few observations in OP1 show that the building model was used only initially for a project review. Later, during the last two projects, OP3 and OP4, the building model was more the centre of discussion and was continuously used to better understand the best sequencing of the activities, highlighting how the building model had become more integrated into the process. However, the participants mainly relied on drawings, documentation, and sticky notes to create their activities.

It could be argued that during the seven years these observations were conducted, the maturity of building models and understanding of the information in these models has increased. However, the user still relies primarily on traditional documentation rather than the model. From the observations, it could also be noted that even though the users' competencies have increased, there is still a dedicated person handling the building model, hinting at problems or at least a reluctance to use these tools. During the last observation, this was one of the contractors' forepersons, a project engineer. The most significant difference between the initial and last observations was how the participants understood and integrated querying the building model in their workflow while planning and scheduling. The building model was visualised in a pure model viewer rather than a scheduling tool, thus exemplifying passive use of the building model.

While it can be concluded from the observations of the CPP process that there has been an increase in the use of BIM in general, this does not tell anything about how collaborative these tools facilitating BIM are. Recent research shows that there is a need for more collaborative planning and scheduling tools (Campagna-Wilson and Boton, 2020).

In the last two evaluations, the participants mentioned the increased technological burden in construction, with a vast set of software to use and utilise; this could raise the question if the tools are easy enough to handle for everyone. Aside from the usability of tools, the participants of evaluations #14 and #15 stressed a lack of collaborative tools as well as problems with interoperability between tools, an argument in line with Campagna-Wilson and Boton (2020), showing that even with the current set of tools, there still is a need for collaborative planning and scheduling tools and that existing tools do not fully address the characteristics and requirements found, as presented in Paper III.

Paper III and IV also brings 4D into the process and shows how the VPP-system differs from traditional 4D software. The literature describes 4D as a passive tool, where finished schedules are merged with models, creating visualisations, but also ask for more collaborative approaches to 4D modelling (Eastman et al., 2011; Campagna-Wilson and Boton, 2020; Boton, 2018). The use of 4D, and VR, as seen in Paper III and IV, shows how collaborative approaches in VR constructability analysis can be compared to planning in the CPP process. Drawing on research in collaborative VR and knowledge sharing (cf. Johansson and Roupé, 2019, 2021), similarities with collaborative planning and scheduling can be drawn. From observing the VR sessions in Paper III, constructability analysis and identifying challenges in the model had a strong focus. These challenges are also reflected in the scheduling, and during the VR sessions, the planning was actually discussed and adjusted even though this was not the main focus.

The VR study shows that given the right tools, the barriers are lowered for interacting with the information, a better understanding of the project, in general, is gained. The users can review the building objects and their position on a real-world scale in VR, enabling a better understanding of limitations and possibilities connected to the schedule. It also enables a review of the schedule in VR on a real-world scale, furthering the possibilities to adjust and approve sequences of the schedule.

Enabling participants to more accessible take part also moves the activity of the participants. ICT tools such as 4D planning tools enable passive visualisation of the schedule, but as seen in literature, (cf. Boton, 2018), it still lacks collaborative properties even though 4D generally is seen as beneficial for communication and review of the schedule. Thus, there are opportunities to take traditional 4D planning from passive to active scheduling. Paper III and IV brings these opportunities and shows how collaboration in 4D is manifested in VR through an Application Program Interface to the VPP-system.

Concluding the discussion above regarding RQ 2 argues how ICT and BIM could support collaborative planning and scheduling, but this also raises questions regarding the design and implementation of such a system. The design and implementation are addressed in the next section.

6.4. The design and implementation of the VPP-system

One of the significant contributions of the thesis is the documentation of the CPP process, as seen in Paper-II. The observations and the documentation shows the collaborative planning and scheduling approach as practised and may help future research compare and contrast developments in collaborative approaches. The analysis in Paper-II helped form the requirements according to the DSR approach. Early in the research, it became evident that the CPP process seemed functional and backed by literature, even though it was not consciously derived from literature. As seen earlier, challenges of IT implementations in construction and especially in production are prevalent (cf. Campagna-Wilson and Boton, 2020), leading to the conclusion that there was a need to keep as close to the CPP process as possible.

Thus the developed VPP system keeps the CPP process but the medium for creating the schedule changes. The implementation is changed by keeping how the planning and scheduling are conducted but evolving the tools supporting the process. The change is from sticky notes to a digital collection of boxes of activities, representing digital sticky notes directly correlated to the building model. The DSR approach meant that rather than beginning with designing and focusing on a routine design from best practices, the DSR approach brought the users in focus and helped focus on understanding the practice and environment together with best practices from the knowledge base. Thus, the planning process is not changed, only the medium of the planning session.

By keeping the process, working familiarity was sustained, allowing for the slight disruption of digitalising the process introduced. From the evaluations, especially of the sessions with participants proficient in the CPP process, it could be seen that focus was shifted from understanding the location and interpreting drawings of the location, as observed in the CPP process observations, to understanding the planning and scheduling problem itself.

Furthermore, the VPP-system strives to adopt a contextualised interface for the scheduling system, displaying fewer options compared to common desktop scheduling systems and instead focusing on the task at hand in the process. By reducing menus and options in the interface, the users can focus on the crucial task, creating, sequencing, and reviewing activities and the schedule. Evaluation #14 exemplifies how even a computer sceptical site manager readily used the VPP-system. The site manager even commented on how other construction ICT tools were cumbersome and how the SM often deferred these to younger, more technology versed engineers.

Comparing the VPP-system to other 4D systems, the VPP-system allows for direct interaction and adjustment of the schedule, even in VR, thus allowing for collaborative planning, as seen in paper III. While these developments are early on, they show great potential to further the understanding for the participants using the VPP-system. During the last two evaluations, it was shown that the participants could collaboratively plan and sequence the schedule, check the sequence directly as it was planned and then re-structure the schedule as needed. This shows that the VPP system creates the collaborative 4D modelling environment that literature identifies as missing (cf. Boton, 2018).

Thus it is shown that through the requirements derived in RQ 2 from the observations with regards to RQ 1, the VPP-system could develop as an instantiated version of the CPP-process through the design cycles of the DSR approach. The DSR approach contributed to the process mapping of the collaborative planning and scheduling approach, which brought a better understanding of why and how the implementation should be done to support the requirements defined through RQ 1 and RQ 2.

An integral part of Design Science Research (DSR) projects is the evaluations and what is learned from the new artefact and the instantiation in its problem context; this is what the next section will discuss through RQ 3.

6.5. New understanding and developments of collaborative planning and supporting systems

Research question RQ 3 are framed to explore what we can learn from the artefacts used. As seen in Paper IV, fifteen observations were done in different iterations and stages of the artefact prototype. As mentioned in Chapter 3 Research Design, the evaluations were either explorative or confirmative.

Since the projects used for observations were rather large, the project's commitment to test and use a newly developed system was rather steep and not feasible, resulting in a limited implementation and evaluation. The incremental development meant that we used an explorative approach to development, evaluating the VPP-prototype in small batches, as seen in table 3.2, where the prototype numbers are visible for each evaluation.

The small increments in the prototypes are indicative of minor revisions of the prototype between the evaluations. This helped the explorative evaluations focus on specific functions of the VPP-system and evaluating usability against the requirements. Early evaluations focused on getting the general usability to an acceptable level. One of the early evaluations showed that while the building models gives spatial and visual information, the information may be subdivided into an unmanageable amount of parts visibly. Thus, alternative ways to interact with the building model and its data was developed, allowing for filtering data in a pre-selected area. In this way, the users could manage more extensive sets of visual data and still manage to create activities efficiently. This filtering function later helped emphasised the need to populate the model with clear and concise meaningful information for the user, as stated by the site manager in evaluation #14 in Paper IV.

The site manager mentioned that the codes and marks used by designers and engineers in the design and stipulated in the BIM manual were too hard to interpret, needing dictionaries to translate to useful information about layers or construction of a wall type or similar, showing how different the participants of the project view the information. The VDC engineers and BIM managers focused more on this type of information since they are used to perform quality control or takeoff of the model. However, as seen with the site manager, the evaluators closer to production and performing the work onsite wanted more direct information. Here the complexity of the use of

BIM is visible; while a BIM model enables an information-rich environment, it is also challenging to expose the right amount of information not to overburden the user. This challenge is also part of the cognitive load discussion touched upon earlier.

Paper IV also shows how the middle managers such as project planners and VDC managers focused more on functions and methods aligning to their scheduling systems such as Primavera, power project or existing BIM tools such as Solibri. From this perspective, the VPP-system is more disruptive for these roles than to the production personnel onsite. The key aspect for these groups is that they are further from the work to be performed onsite, although their job is to manage and coordinate the information delivered to the production personnel. The VPP system also more closely resembles the work processes conducted onsite since it is modelled on these processes. Thus, the VPP system is less disruptive for the production personnel, especially with persons familiar with the CPP process. These findings are supported through the observations, as seen in Paper III and IV.

What also became apparent throughout the research project was the access to different participants. Production personnel was hard to engage due to their busy schedule. Middle managers, project planners and VDC engineers were easier to engage since they more often drive the development and implementation of new tools.

One could argue that this is solvable through education of the production personnel, but this then becomes a question of reducing waste. As seen in lean literature, a core concept is reducing waste; while educating the production personnel in the use of BIM could be beneficial, it is not value-adding. It may be an indirectly value-adding activity, but it does not help users do their job more efficiently.

The DSR approach, in combination with the size of applicable projects, probably contributed to the fact that a full-scale project evaluation in an actual ongoing project never occurred. A test in an actual project needs to contribute to the project at hand and not duplicate planning work they already had done. There is also a limited number of projects in the region using the CPP process, which limits the possibilities.

The DRS approach helped identify the role and importance of the production personnel in the evaluation and implementation of new tools. VDC and Project planners the driving force behind the implementation of new tools.

Also seen during the evaluations, especially in the last evaluation, was how the VPP-system could be used in other settings than the CPP process it was developed for. The system supports both push and pull-planning, and as such, could be used as a last planner planning tool, enabling a broader generalisability of the VPP-system to construction outside the Swedish and Scandinavian context and the collaborative consensus culture seen here (cf. Bröchner et al., 2002).

7. Conclusion

The twofold aim of the thesis has been; (a) to study a production planning and scheduling process in use in Scandinavia and (b) design, develop and evaluate a user-centric collaborative planning and scheduling system with the use of BIM. The research is manifested through the three research questions.

The first question RQ 1 - *How is a collaborative planning process performed in construction production, and especially in a Scandinavian context?* is mainly addressed through the observations of the Collaborative Production Planning (CPP) process and the description and documentation of this process in Paper I, II and III. The observations, albeit limited, further indications found in the literature that BIM use is limited (cf. Sundquist et al., 2020). Furthermore, the observations indicate that the collaborative planning and scheduling process is known in the industry.

The documentation and analysis of the CPP process have provided a deeper insight into the practice of the planning process, which serves as knowledge added to the field of collaborative planning and scheduling. The research shows that collaboration and empowerment have a clear role in production management and control, not only in Scandinavia but also in general.

The second question RQ 2 - *In what ways can ICT for visualisation with building models support collaborative planning and scheduling?* is answered through Paper II, III and IV where scheduling and visualisations such as 4D modelling, visualisations and simulations are identified and exemplified as ways ICT could support the planning and scheduling process. Furthermore, the literature highlights the shortcomings of these types of approaches. The need for the ICT system was identified through observations of the practised CPP process. The final requirements, however, was derived both from the observations and the literature concerning scheduling, modelling and visualisations and CVE.

Together with the documentation, the developed Virtual Production Planning (VPP)-system can be a step in the direction of lessening the perceived fragmentation and embrace collaboration. The papers also show that the VPP-system has the potential to go beyond this.

Thus, answers to research question RQ 3 - *What new insights could be gained from integrating building models in the planning and scheduling process?* is partly answered already from the answers in RQ 2. This question was mainly answered through the evaluations. It was found that the VPP-system improves the engagement of the participants in the planning, making participants more active during the planning and scheduling, increasing ownership of the schedule as well as increasing the overall project understanding. The evaluations also indicated that the system is more in line with how the site management and workers work currently and thus less disruptive than for the middle management, planners and VDC managers. The VPP-system also showed indications of reducing cognitive load by focusing on value-adding activities in the observed planning and scheduling process, thus reducing the length of the collaborative planning sessions. Furthermore, schedules can be reviewed instantly without translation from physical draft to digital, further reducing the potential length of the collaborative planning sessions. The VPP-system also reduces the need for co-location, even though it still is beneficial. Thus, the VPP-system enables more ways of collaborating and enables remote participants.

7.1. Implications for practice

The developed VPP-system is in itself a contribution to the practice. The implemented VPP-system addresses the identified gap of collaborative production planning software and shows potential to bridge a gap that previous 4D solutions does not cater to, namely the collaborative and interactive aspects of planning and scheduling.

7.2. Implications for the knowledge base and future research

The collaborative approach to 4D modelling is perhaps the most significant contribution to construction planning and the construction management body-of-knowledge. The manifestation and development of the interactive, collaborative 4D modelling and scheduling approach is a clear contribution combining dispersed areas such as planning and scheduling, BIM, and the use of VR both on screens and in head-mounted displays.

The use of the Design Science Research (DSR) approach is in itself a contribution to the body-of-knowledge of Construction Informatics (CI). Furthermore, the modelling of the different planning processes is also a contribution to CI, as it provides a certain amount of comparability for future research into similar planning processes.

Judging from the evaluations and discussions with participants along with the research project, possible future areas of interest could be:

- to follow the implementation of the VPP-system in an actual construction project, further evaluating the effects of the VPP-system in practice.
- to explore a collaborative planning approach using the VPP-system in early stages of projects, such as design development.
- to explore the possibilities of a collaborative planning approach using the VPP-system in other types of projects, like infrastructure.
- to extend functionality to enable immersive 4D modelling in VR and explore the effects,

for example, constructability issues identified in the planning process.

- to extend functionality to enable follow-up of the work, study how the VPP-system could help the project participant better understand the project's current status and identify possible challenges concerning current status compared to planned progress.
- to extend functionality to explore how the bid process can be incorporated in the VPP-system and how this could affect the planning in pre-construction, possibly enabling comparisons between bids and between the bid and the actual plan.
- to explore how the VPP-system could facilitate knowledge management sharing between projects, how the database could facilitate, for example, bid evaluation, and help identify risk in activities by comparing the duration of similar older activities.
- to explore increased remote participation and the effects on the planning process.

As seen above, there are plenty of options going forward, both looking towards the design and bid phases and the daily and weekly planning work onsite. It has been an exciting journey over the past seven years, and it seems that the use of building models, VR, HMDs, augmented and extended reality is just beginning to develop.

The fragmentation and specialisation of the construction industry may not have a single solve-all solution, but the thesis is a piece of the puzzle in addressing these issues. This research can be a cornerstone in much work to come.

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