Exploring challenges with reciprocal interdependencies in 4D BIM

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Abstract

This paper explores how the utilization of 4D BIM can bridge the gap between actual and planned progress. The preparation of progress plans usually occurs when limited information is available, which entails revisions of schedules when new information emerges, and actual progress deviates from planned progress. When moving from pooled to sequential to reciprocal interdependencies, there is a need for more complex communication and coordination in order to prevent difficulty in obtaining information, completing tasks, and decision-making. The key to successfully using 4D is to avoid negative iterations by downscaling and planning more schematically. This includes task detailing and breaking down reciprocal interdependencies into pooled and sequential interdependencies. The findings of this conference paper indicate that increased utilization of 4D is limited due to the lack of an organizational culture investing in standardized policies and procedures for digital solutions to reveal the capability and capacity in 4D BIM-based systems.

Keywords: 4D, Building Information Modeling, Planning Process, Reciprocal Interdependencies.

1 Introduction to Challenges with 4D BIM

The construction industry is facing significant challenges in light of the digital shift. Nevertheless, there are many possibilities to improve the construction process through the digital representations of physical artifacts. Building Information Modeling (BIM) has emerged as a paradigm shift in the industry towards its digital transformation. Moreover, BIM-based tools can be very beneficial for seamless scheduling, planning, and real-time schedule adjustment. Construction projects are often delayed for a variety of reasons. It is a well-known phenomenon that the construction industry regularly fails to meet the targets for completing projects on time. It can be very complex to estimate the actual time needed to construct an artifact accurately. The decomposition of a project into phases, deliverables, work packages, and activities is necessary for schedule development and control. It is crucial to look closely at the different activities, the sequencing of the different activities, and their duration for detailed project and task planning during the planning process. Activities should be based on a carefully formed work breakdown structure that considers how every artifact is unique with a specific set of objects. Understanding the amount of time a project requires is a crucial part of project planning. Utilizing 4D BIM for holistic and effective planning brings forward a new construction innovation in the digital era.

BIM is a subject area that addresses the increased use of IT, interoperability, and digital collaboration within project-based organizations. This paper considers 4D BIM and its impact on planning and scheduling. The concept behind 4D BIM is integrating project data related to the time schedule systematically in a 3D model. Expanding BIM dimension from 3D to 4D supports the timely completion of projects by monitoring and controlling the construction schedule (Sacks et al., 2018). Time is one of the most precious resources available in a project. Adding the fourth dimension to the BIM model offers an opportunity to evaluate the constructability and workflow of progress plans. 4D BIM is becoming a contractual requirement in most large-scale infrastructure projects in the Norwegian construction industry. This study aims to identify how the use of 4D BIM in the planning and scheduling of projects can lead to a greater understanding of the progress of the construction work. Despite the potential, 4D BIM is not widely used in the Norwegian road construction industry because it is not a client requirement in most projects.

Digital transformation makes it possible to plan, design, and build artifacts more efficiently and improve artifacts' operation and maintenance. Using digital tools to test, simulate and analyze what is to be built can enhance the productivity and performance of projects. One of the benefits of digital transformation with 4D BIM is visually showcasing the schedule's critical path, which can help actors quickly grasp the project's current schedule status against the 4D model. Making use of progress plans to retrieve the right information for the right purpose delivered in the right format to the right recipient at the right time is a prerequisite for efficient project execution. The root causes for project schedule overruns and delays in project delivery can be attributed to factors such as silo working, lack of coordination and collaboration, inefficient planning, and construction practices that can lead to waste, re-work, and reduced productivity. 4D can also be used to communicate and coordinate dependencies between tasks (Hartmann & Fischer, 2007). This enables the actors to simplify the nature of the construction work and better manage it by changing the reciprocal interdependencies into pooled and sequential interdependencies.

Despite recent advances in 4D BIM implementation in Norway, there are still many challenges to overcome. The tools are currently available. However, a broader understanding is required to put the tools to work effectively in the best interests of client organizations, contracting companies, consultancy agencies, and stakeholders alike. This paper presents an overview of the current 4D BIM research fields, trends, and business strategies to overcome those challenges and promote the digitalization of the Norwegian road construction industry. This paper's research questions are aimed at uncovering this by exploring the challenges related to interdependencies. The use of 4D BIM research questions (RQn) for this paper can be listed as follows:
RQ1: *What are the challenges in 4D BIM related to pooled, sequential, and reciprocal interdependencies?*
RQ2: *How do the different types of interdependencies influence the utilization of 4D BIM in a project?*

This paper about challenges related to reciprocal interdependencies with 4D BIM is structured as follows: Chapter 1 sheds light on the background of the paper and introduces the research topic; Meanwhile, the theoretical framework related to the research questions are presented in Chapter 2; Furthermore, Chapter 3 describes the case study project and the methodological choices that were made to collect and analyze data; Next, the findings from the data collection and analysis are summarized and discussed in Chapter 4; Finally, the conclusion to the paper is presented in Chapter 5.

2 Existing Theories and Previous Work

This chapter presents findings from relevant literature to increase the understanding of 4D BIM.

2.1 Understanding Building Information Modeling

BIM is a shared digital representation of an artifact that provides a semantic representation of topology, components, and properties. The term can be described as a set of tools, processes, and technologies that facilitate design, construction, and operation processes to form a reliable basis for decision-making (Sacks et al., 2018). BIM is enabled by digital machine-readable documentation to provide the basis for new construction capabilities and changes in the roles and relationships among actors (Sacks et al., 2018). The roots of BIM can be traced back to the late 1970s and early 1980s (Azhar et al., 2012). However, the construction industry did not fully implement BIM in projects before the mid-2000s. During the last few years, BIM has gone from being merely a buzzword to being implemented broadly into the construction industry as a contractual obligation in most large and complex projects (Azhar et al., 2012). There is an increased effort to apply this technology, even though there are many challenges due to the high effort needed to gather and create the necessary information in digital building models.

BIM is one of the enablers and most highlighted digitalization initiatives in the construction industry (Hjelseth, 2017). BIM is used to coordinate complex projects since it can support more accurate and efficient management processes, thereby enhancing collaboration and information-sharing (Azhar et al., 2012). The lack of communication and coordination in construction projects has consequences such as non-uniformity and misapplication of resources, thus increasing the construction time (Charlesraj & Dinesh, 2020). Some of the potential advantages of BIM are improved construction performance, quality, and project delivery times, in addition to reduced project costs and earlier visualization of the design (Baldwin & Bordoli, 2014). Additionally, the advantages include the prevention of detailing errors in design and poor specifications of deliverables. BIM can integrate project data into 3D building models systematically. This includes project data related to the project life cycle and construction schedule. BIM can be used for 3D modeling, quality checks, quantity take-offs and calculations, as well as visualization, monitoring, and control of the production system (Baldwin & Bordoli, 2014). Creating and deploying intricate and intelligent digital building models can help carry out projects within the planned time frame.

2.2 Interdependencies in the 4D Planning Process

The progress of a project is often expressed in terms of the percent completion of activities (Kim et al., 2013). By comparing the actual progress with planned progress, deviations can be detected, and each activity's actual start and finish dates can be more accurately determined. Activities in traditional scheduling concepts such as Gantt Chart, Linear Scheduling Method, Critical Path Method, and Program Evaluation and Review Technique are not directly linked to the objects in the digital building model (Charlesraj & Dinesh, 2020). 4D planning is an extended and deeper version of conventional planning that develops the construction planning to a higher level of detail to provide greater accuracy and less risk (Charlesraj & Dinesh, 2020). 4D visualization allows for a more intuitive comprehension of the construction process than traditional 2D drawings and schedule information (Sloot et al., 2019). With 4D BIM-based software, the intent is to connect activities to objects in the BIM model, enabling the sequencing of the construction process. The fourth dimension of BIM allows actors to extract and visualize the course of the activities throughout the project's life cycle (Sheina et al., 2019). Visualizing the construction works allows actors to get an overview of the overall construction process, including all related factors and potential consequences, in addition to the various details. By utilizing 4D BIM, actors can pre-determine the optimal option through activity sequencing and model simulation.

The 4D modeling method was developed in the early 2000s (Sheina et al., 2019). On the one hand, it turned out to be in demand, and on the other hand, it was too complex for widespread implementation due to the process of creating 4D models being very information-intensive. A 4D model cannot exist without a detailed 3D model, and the developed 3D building model is the basis for the 4D model (Sheina et al., 2019). 4D BIM tools incorporate time-related information into the 3D building model to graphically simulate the sequence of construction operations (Sloot et al., 2019). The actors' capability and capacity are critical when designing a 4D model during the planning process to ensure constructability (Charlesraj & Dinesh, 2020). 4D BIM-based scheduling provides time estimation and visualization, and 4D BIM tools facilitate the planning process through better construction planning. 4D is especially beneficial for real-time measurement, assessment, and interpretation of project status (Sacks et al., 2020). Also, 4D process planning simulations serve as a communication tool to identify potential bottlenecks in the production through activity clash detection, thereby improving coordination between actors.

According to Politi, Aktaş & İlal (2018), some important uses of 4D BIM are visualization, clash detection of activities, and sequencing of the construction process. These are applications of BIM that make it easier to understand the dependency which various activities have on each other. The relationship between tasks can be grouped into pooled, sequential, and reciprocal interdependencies that apply for construction works (Thompson, 1967; see also Jin & Levitt, 1996). The different types of interdependencies are presented in Figure 1. The level of communication, coordination and collaboration among actors required to complete the tasks effectively increases from left to right in the figure. According to Jin & Lewitt (1996), pooled interdependencies are most desired since they significantly reduce the coordination complexity during construction. It can be challenging to get an overview of the interdependence in large and complex projects during planning. However, the complexity can be more easily handled with the Cynefin framework, which is a sense-making device used to aid decision-making (Kurtz & Snowden, 2003). The 3D model makes it easy to conceptualize the design intent and can be utilized by stakeholders to inform and communicate in the design and construction phase (Azhar et al., 2012). By performing activity clash detection, it is possible to identify interferences and validate designs without affecting compliance (Häußler & Borrmann, 2020). This makes it possible to save a lot of time during the construction phase. The 4D model can plan, schedule, and simulate the construction process, thereby making it easier to manage the material ordering, fabrication, and delivery schedules for all installations, components, and equipment (Azhar et al., 2012). Some other areas of use for 4D BIM are documentation and claim analysis in case of delays, work progress meetings supported by 4D models, validation of time schedules by simulations, location-based planning, site-layout planning, and logistics planning (Charlesraj & Dinesh, 2020).

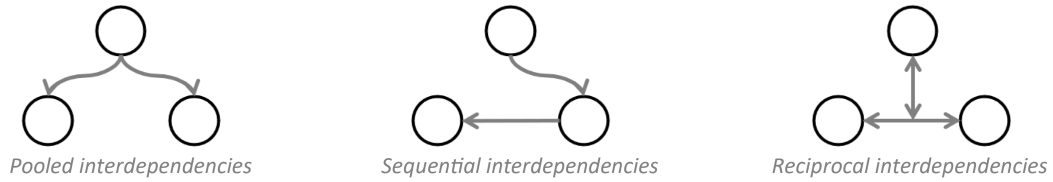

Figure 1. The classification of the different types of interdependencies that are addressed in this paper.

3 Case Description and Applied Research Methods

This chapter describes the methodological choices made during the writing process of this paper.

3.1 Focus on Digitalization in the Case Study Project

This paper is a single case study of a large-scale infrastructure project in which 4D BIM is utilized to mitigate planning and scheduling risks. The case study project used for collecting data in this paper is an ongoing large and complex culvert and tunnel project in Norway. The client organization is a government agency responsible for owning, maintaining, operating, and developing infrastructure in Norway. They have selected one of the larger Norwegian contracting companies to provide both the design and construction of the artifact. We have chosen to anonymize the involved actors and stakeholders in order to present internal practices related to the project organization's use of 4D BIM. This research aims to document experiences from the case study project to capture lessons learned from both the client and contractor perspectives. In the long run, this can be beneficial to future projects with a focus or demand for 4D BIM.

The client organization is known to give high priority to digitalization and innovation in its infrastructure projects. Therefore, the client organization has required the main contractor to utilize 4D BIM to reduce and eliminate progress uncertainties in this culvert and tunnel project. The main contractor in this project uses 4D tools to prepare progress schedules and 4D models to visualize the construction progress. The contractor's schedules state the main activities and the other activities on which these are dependent, whether pooled, sequential, or reciprocal dependencies. This is further visualized in the contractor's 4D building model. The project organization considers 4D BIM an important success factor in the communication and collaboration between the client organization and the contracting company. The main contractor informs the client organization of the status achieved compared to the progress schedule and notifies the client organization whenever actual progress deviates from planned progress. In addition, the contractor assesses constructability by using 4D to document how the company executes the construction work and limits the consequences for stakeholders. In this way, the main contractor can ensure that the on-site activities occur rationally and without delays.

This study emerges as the result of a partnership between industry and academia. The main contractor requested the authors of this paper to conduct research on the contracting company's behalf as a third party to measure their 4D implementation, thus uncovering the missing link to achieve holistic understanding and utilization of 4D BIM in construction planning and scheduling.

3.2 Applied Research Methods

It is imperative to choose a suitable research method to acquire the essential knowledge to answer the research questions. The research method selected to acquire the knowledge provides guidelines for how theoretical and empirical data are obtained. A vast number of choices must be made in a scientific study in connection with the research method, ranging from the choice of the scientific theoretical starting point to how collected empirical data is to be analyzed.

This case study uses an explorative and interpretative research approach focusing on qualitative techniques and thematic analysis to collect data and analyze empirical data. The paper's qualitative techniques include ten semi-structured interviews with actors from the client organization and contracting company, five group discussions, and participating in five progress meetings with the contractor. The actors involved in the case study include design managers, site managers, operating managers, production managers, production planners, project engineers, and BIM technicians. Furthermore, a literature overview was conducted to gather even more data. Given the research objective, literature that focused on planning and scheduling was explored and reviewed to identify research needs. A case study was conducted to understand how the main contractor's use of 4D BIM supports the planning process in this project. The case study research method is used to understand a complex phenomenon, and it allows researchers to retain the holistic and meaningful characteristics of contemporary events (Yin, 2018). Case studies are used when it is difficult to understand a phenomenon without knowing the full context. Additionally, case studies are used mainly for qualitative research methods. The authors of this paper had a very hands-on approach as researchers in the project and were involved for a period of six months. Therefore, this is a longitudinal study with an emphasis on triangulation with the application and combination of several qualitative techniques over an extended time period.

3.3 Research Model for Analysis of the Results

There are many ways to conduct research and there are many forms of data. The empirical and theoretical data that is collected for this paper had to be analyzed and interpreted. Analysis of qualitative data from the semi-structured interviews, group discussions and observations from the progress meetings consisted of processing text. Therefore, the qualitative data analysis software NVivo® with thematic analysis was utilized to organize and analyze the empirical data.

The key findings of this paper will be presented by utilizing the mindset from the Integrated Design and Delivery Solutions (IDDS) framework. The IDDS approach is used for exploring the dominating understanding of BIM (Hjelseth, 2017). The IDDS framework addresses how the construction industry can change and improve performance by adding value through collaborative people, integrated processes, and interoperable technology (Prins & Owen, 2010; see also Owen et al., 2010). Figure 2 illustrates the ideal relationship between the different aspects of IDDS. The different aspects are equal in size, equally important, and overlapping in the center of the figure. By using the IDDS framework, this case study will identify the integration between the following: (i) collaborative people (a multi-disciplinary collaboration that ensures expertise in taking advantage of 4D models), (ii) integrated processes (the use of standardized policies and procedures for 4D BIM) and (iii) interoperable technology (user-friendly 4D tools for modeling of the construction works). This integration is crucial for the implementation of 4D BIM in project-based organizations. The elements for implementing 4D BIM, such as drivers for change, enablers, barriers, and opportunities, will be presented and discussed in the next chapter.

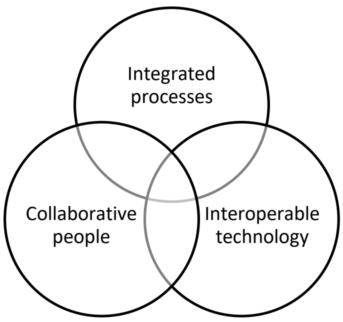

Figure 2. The different aspects of the IDDS framework. Based on a simplified version from Owen et al. (2013).

4 Findings and Discussion

This chapter summarizes the collected data that is required to describe the research questions.

4.1 The Collected Data

In order to understand the challenges of 4D BIM in this case study project, it was important to get an overview of the combination of people, process, and technology. Thus, the IDDS framework was used to map drivers for change, enablers, barriers, and opportunities regarding 4D BIM. We used Appendix A from Owen et al. (2013) as a reference point to uncover specifically which drivers for change, enablers, barriers, and opportunities were the most relevant for 4D BIM implementation in the case project. According to the empirical data collected and analyzed, some aspects from Appendix A were highly applicable to the culvert and tunnel project. The key findings from the data collection that match up with Appendix A are summarized in Table 1. A more detailed interpretation of the table contents is presented in the following subchapters.

Table 1. An overview of drivers for change, enablers, barriers, and opportunities. Based on Owen et al. (2013).

Drivers for change	Enablers	Barriers	Opportunities
Government Demands	Collaborative Development	Resistance to Innovation	More Reliable Outcomes & Improved Profits
Innovation Imperatives (Market Differentiation)	Visualization Technologies (Including BIM)	Change as Risk Instead of Improvement Opportunity Option	Reduced Time Waste in Construction (Re-design & Re-work)

4.2 Analysis of the Collected Data

Table 1 is used as a starting point for analyzing the findings from the case study research. First, the relevant drivers for change are discussed, and secondly, enablers are the topic of discussion. This is then followed up by barriers, and lastly, the opportunities that 4D BIM brings forward. The information below is obtained from interviews, group discussions, and observations.

4.2.1 Drivers for Change in the Planning Process

Government demands lay down the ground rules for an infrastructure project. There is no indication that Norwegian contracting companies want to utilize 4D BIM by their own accord because it is very resource-intensive to create and update 4D plans and models. Therefore, client organizations have to set strict requirements for 4D BIM in infrastructure projects to impose contracting companies to utilize 4D in planning and scheduling. However, those who make requirements must also have the capacity and capability to follow up on the requirements. It can be challenging for the contractor to reap the benefits of 4D BIM if the client does not set clear goals and objectives for using 4D BIM-based systems in the project. Additionally, the client must specify how 4D should be used to ensure a common understanding with actors and stakeholders. Expanding BIM dimensions from 3D to 4D is a considerable innovation imperative. Therefore, clients should encourage competitive innovation between actors. Contractors with 4D expertise can stand out among other skilled contractors using a more traditional project planning and scheduling approach. With that in mind, contractors should strive for innovations and grasp where the opportunities for differentiation in the market occur to gain a competitive advantage.

4.2.2 Enablers for Implementing 4D Planning and Scheduling

Collaborative development demands further consideration and monitoring to meet target schedules and increase production. Collaboration is about developing a generic project planning and scheduling process bespoke to the selected 4D BIM-based system in an infrastructure project. This development of standardized policies and procedures with 4D BIM has to be a collaborative effort from different actors and stakeholders alike in order to uncover the different information needs and digital competencies. The key to the successful implementation of 4D planning and scheduling depends on close collaboration at the outset with the client organization, contracting companies, consultancy agencies, and stakeholders alike. 4D digital tools enable design, integration, optimization, and visualization of workflows. In addition, they can help to optimize and validate project plans. BIM technology for visual planning can simulate the 4D sequence. The development of visualization technologies for modeling and simulating all aspects of the construction process has emerged as a new range of BIM technologies. BIM is a crucial part of determining the construction sequence and digital building models make it very easy to consider any assumptions about the order and priority of the activities in the construction process.

4.2.3 Barriers for Adopting 4D BIM-based Systems

Resistance to innovation can be a significant barrier to the successful implementation of 4D planning and scheduling, regardless of whether the innovation is entirely new or significantly improved. Construction companies are not always eager to invest in new solutions and project methodologies since they require time and effort to successfully implement. An innovation requires implementation, either it is in use or made available for use, and appointed actors have specific responsibilities towards the innovation and must facilitate the implementation. Therefore, digital transformations can be very resource-intensive since innovations require up-close and in-depth learning and maturity. Resistance to change in large and complex infrastructure projects is due to high-level novelty, complexity, and uncertainty. Changes are often associated with significant risks instead of improvement opportunities. Making use of 4D BIM requires creativity, experimentation, and both negative and positive iterations. Therefore, resistance to change is a natural risk-averse reaction. A culture change is needed to view change within the planning process simply as an improvement opportunity instead of significant risk.

4.2.4 Opportunities When Utilizing 4D Models

The idea behind reliable project outcomes and improved profits is to keep the planned and actual start and finish dates of activities dependable by improving the planning process with 4D BIM. It is very beneficial for contractors to evaluate risks and opportunities that impact the necessary time, cost, and quality to complete the construction work, which provides a more predictable project outcome during project execution. 4D models make selecting optimal options regarding the commencement of the different activities and their duration much easier. Additionally, 4D makes it possible to measure the progress of the different activities and revise construction schedules in the case of deviations. This can bridge the gap between actual and planned progress. 4D BIM also can reduce time waste in infrastructure projects by preventing re-design and re-work. Mastering BIM in planning and scheduling can prevent the generation of waste that results in delayed project delivery, cost overruns, reduced quality, and litigations. These opportunities are due to 4D planning and scheduling being able to identify disruptions to the construction work and delays due to inadequate information, communication, and collaboration early on.

4.3 Discussion of the Findings

There is an increased focus on the time factor in BIM-based systems to improve construction performance. In this culvert and tunnel project, the main contractor successfully took advantage of 4D BIM to visualize the site-based planning process. Hence, planning on a high level was achieved. However, the contractor struggled to implement detailed 4D scheduling, sequencing, and simulation without guidance from the client organization. Significant variations and disturbances in the planning process made it difficult and time-consuming to develop and update 4D models because there was a need to update over-optimistic construction schedules continuously. The deviations between actual and planned progress were so significant that the construction schedules did not represent the executed construction work. This is primarily due to silo working, lack of coordination, and collaboration when creating the 4D plans and models.

The general experience was that the use of 4D worked very well for planning in the earlier phases of the project. 4D was very useful in giving an overall understanding of the sequences of the different building sections. It also worked very well for profiling and marketing, and gave a good general overview to the actors and stakeholders. However, when the project's complexity increased, the usefulness of 4D BIM dropped radically, as presented in Figure 3. Our analysis connects this to pooled, sequential, and reciprocal relationships, simply because complexity requires information. The need for information in order to manage interdependencies increases from pooled, sequential to reciprocal. As illustrated in the figure, there is a significant drop in value creation when planning reciprocal relationships. 4D BIM is not suitable for reciprocal interdependencies as it requires a high degree of detail in the software, which is very time-consuming and difficult to achieve. Prior research from Hartmann & Fischer (2007) presents how 4D models can help change reciprocal interdependence between construction activities into pooled and sequential interdependence. In this figure, we have also presented how this relates to the Cynefin framework. When tasks get too detailed and yields become too small, actors tend not to use the 4D models since it becomes too challenging to navigate the models and the input of information becomes too intricate. This is related to both the manual information flow from the actors and the functionality in the software to process reciprocal relationships. In order to prevent re-scheduling and project delivery delays, reciprocal interdependencies need to be handled better. In this project, there was a lot of room for improvement to utilize 4D BIM fully.

The complexity in infrastructure projects can be more easily managed with the Cynefin framework. This framework consists of the following domains which are relevant to this paper: (i) clear (cause and effect are known), (ii) complicated (cause and effect can be known), (iii) complex (cause and effect are not known) and (iv) chaotic (cause and effect can not be known). As complexity in interdependence increases, there is a drift from the clear domain through complicated and complex to the chaotic domain. This is also shown in Figure 3.

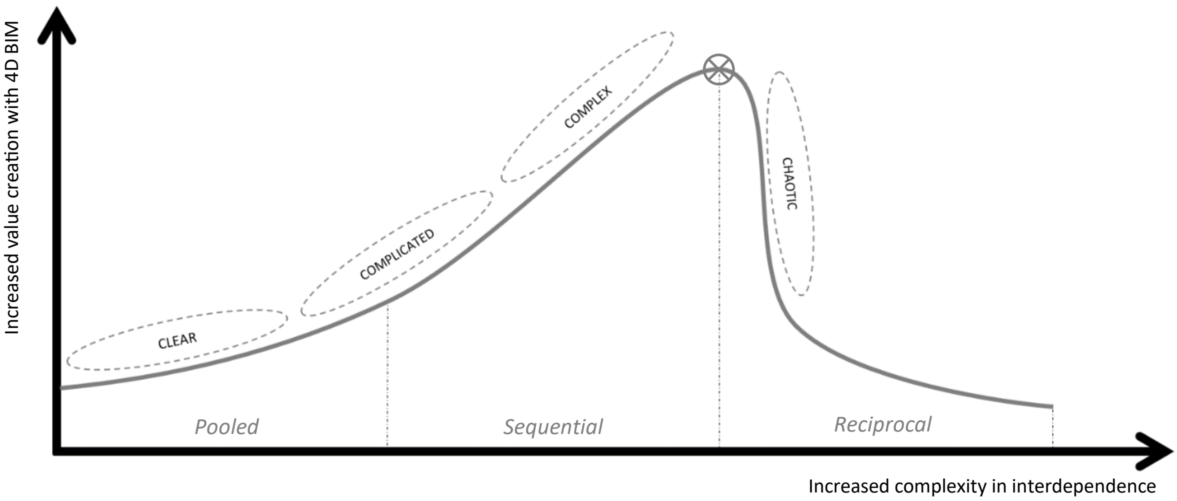

Figure 3. Graph showing the relationship between value creation with 4D and complexity in interdependence.

Our findings show a disconnect between integrated processes and interoperable technology for the case study project, as presented in Figure 4. The culvert and tunnel project has experienced a lack of organizational processes that support the use of new and unknown technology such as 4D software. The aspect of collaborative people is at the center of a tug-and-war between the 'submissive' integrated processes aspect and the 'dominant' interoperable technology aspect. This hinders the actors from reaping the benefits of a holistic combination of people, process, and technology. This figure is further detailed in the paragraphs below.

Collaborative people: There is a gap between integrated processes and interoperable technology, which is covered by the capacity and capability of the project organization. Multi-skilling people ensure project success by preventing problems and developing new opportunities.

Integrated processes*:* The organizational processes in the case are lacking, and the project organization does not receive any support from the base organization in adopting innovative solutions. This creates challenges with a fragmented understanding and utilization of 4D BIM.

Interoperable technology: The range of 4D BIM software is decent, but the user threshold for 4D tools is a bit too high. There is no common understanding of how the tools should be used. Additionally, the actors who are responsible for planning are not the ones creating the 4D models.

Having the right people, as well as smart tools, systems, and workflows, is crucial to project success. Thus, a multi-disciplinary collaboration that ensures expertise in taking advantage of 4D models is about having the right people. Meanwhile, using standardized policies and procedures for 4D BIM and user-friendly 4D tools to model construction works is equally as important.

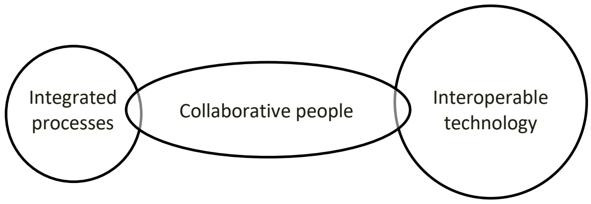

Figure 4. Lack of integration between the following aspects: integrated processes and interoperable technology.

5 Conclusion of the Case Study

This chapter concludes the research questions with the aim of summarizing the research findings.

5.1 Concluding Remarks

Pooled and sequential interdependencies are preferred during activity sequencing due to their simple nature. In the case study, pooled and sequential interdependencies were ideal for visualization and activity clash detection. However, the project organization deemed reciprocal interdependencies too difficult to simulate due to their chaotic nature. 4D BIM has the ability to break down reciprocal interdependencies into pooled and sequential. Therefore, the actors missed out on activity clash avoidance by disregarding reciprocal relationships in the 4D model.

In principle, 4D can increase the validity and reliability of project plans. This study indicates that integrating data for better project control and added value increases project performance with visualization, monitoring, and control of the progress. However, from the culvert and tunnel project, there seems to be a lack of software support and experience transfer in the planning process, making 4D planning very difficult to accomplish. For a contractor to successfully utilize 4D BIM during the construction process, adequate resources from the base organization in the form of experienced project participants with 4D expertise are required. Otherwise, the project participants must educate themselves on project planning with 4D BIM during project execution through learning-by-doing. This can lead to ineffective use of critical resources. Additionally, inexperienced actors can make mistakes when using 4D BIM tools since 4D modeling is a tedious and error-prone process that requires lots of time and experience with planning and scheduling.

This study demonstrates the need for a more integrated reach for a deeper understanding of the complexity in project-related tasks related to all options available in design and constructed solutions. This also includes multiple and conflicting requirements such as time, cost, quality, and sustainability. Additionally, the case study demonstrates the need for a new type of professional digital competency. This type of digital literacy at a high level goes beyond the advanced use of software and more towards data integration and systems for information management. Collaboration through digital solutions is not only about good teamwork but also being supported by digital processes. Lastly, the challenges in 4D planning are rooted in solving and resolving reciprocal interdependencies and just-in-time updates of data representing the real world.

5.2 Future Works

There is a great need to conduct further research on the lack of integration between integrated processes and interoperable technology. By uncovering the missing link between these aspects, it will be possible to identify appropriate solutions to change and improve project performance.

Future research within 4D BIM should be seen in relation to ongoing research fields and trends such as the Digital Twin and the Internet of Things to explore the technological perspective concerning new types of integrated processes. This approach embeds a novel understanding of 4D BIM. The Digital Twin concept can further elevate 4D BIM by enabling the digital building models to track, store and display up-to-date project data related to the time schedule by utilizing the Internet of Things. This can include a shift from 4D BIM to more agile 4D technology.

Increased value creation with 4D technology is a driver for change, and further studies should therefore include business models as a part of the management perspective. In principle, 4D technology has the capability to be an integrated part of computational support to Integrated Project Delivery, Virtual Design and Construction, and Lean Construction. This can enable a shift in the way large-scale infrastructure projects are managed. However, currently, we are far away from this ideal scenario and the industry is lacking the right construction management processes.

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[1] MEERC is an acronym for **M**ore **E**fficient and **E**nvironmentally friendly **R**oad **C**onstruction.