MSc. Thesis project

Developing an assessment framework to support the decision-making process for adopting 4D BIM in infrastructure projects

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Strukton Civiel

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PREFACE

Hereby I present my graduation report of the master programme Construction Engineering & Management, a collaborative effort between the University of Twente and Strukton Civiel. This report is about using 4D Building Information Modelling (BIM) in infrastructure projects. The subject of BIM intrigued me during the master programme and Strukton Civiel shared a mutual interest in researching 4D BIM. During my research period at Strukton Civiel, I obtained a lot of practical knowledge about how large-scale infrastructure projects are digitalized to 4D. Worth mentioning was a 4D construction digital conference I attended during this research period. It was very interesting to see how 4D BIM is adopted by practitioners on a global scale. The key takeaway from this conference was that 4D BIM is not about the animations, but about the value it can provide. In my opinion, the true value is improving the communication of information between everybody that is in some way involved with the project. This is one of the many things I learned during my research period and I want to thank everyone that helped me along this journey. Several individuals contributed to this research that I would like to acknowledge in particular.

Firstly, I want to thank my supervisors Arjen Adriaanse and Robin de Graaf for their supportive feedback that challenged me to strive for a better result. Secondly, I want to thank my commissioners Mark Vlaanderen Oldenzeel and Djim Witjes for the opportunity to do this research at Strukton Civiel. They always expressed their enthusiasms towards 4D BIM and provided many useful suggestions during this research. Thirdly, colleagues at Strukton Civiel were always eager to help and provided me with practical knowledge. Lastly, I want to thank all my friends and family that helped me with this report during my research period. Besides, although COVID-19 caused me to do most of the research at home, I was very fortunate to live with roommates who provided me with much needed motivational support during the many coffee breaks at home.

This research project is the final milestone of my years as a student. These have been incredible years and I am very grateful for this experience, which would not have been possible without the help of others!

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SUMMARY

4D Building Information Modelling (BIM) associates object-oriented information of the construction project with time or planning-related information. This technology advancement revolutionized the construction industry over the past 20 years and there are many uses of 4D BIM that may be beneficial for the project. However, project managers have a limited budget at their disposal and implementing a 4D model can be expensive and time-consuming. Whether or not these benefits outweigh the costs of implementing a 4D model depends on the practical situation. Risks concerning safety, design mistakes and schedule delay are for some projects higher than others. For projects where these risks are bigger, the need for a 4D model is possibly higher. And if so, the question arises of what 4D uses should be considered. This assessment is part of the decision-making process of every infrastructure project of Strukton Civiel. This Dutch contractor carries out a wide range of infrastructure projects and is unsure for which projects 4D BIM is interesting.

While literature covers 4D BIM and several different uses, there is a knowledge gap concerning linking 4D BIM and associated 4D uses to different situations in practice. The objective of this research is to overcome this knowledge gap and to contribute to 4D BIM adoption by designing an assessment framework that supports the decision-making process for adopting 4D BIM and its most relevant 4D uses in different practical situations. A design science methodology was consulted to come up with a research method to design the framework. The research method consisted of three phases: problem investigation, design treatment and validation treatment.

In the problem investigation phase, a theoretical and practical study was conducted to determine the most relevant 4D uses for infrastructure projects. The literature study resulted in twelve different 4D uses that are adopted across the entire life-cycle of infrastructure projects. However, literature in terms of practical situations in which these 4D uses are applied was limited. In addition, it was unknown which of these 4D uses were more relevant for Strukton Civiel. Therefore, practical information from Strukton Civiel was gathered to fill this knowledge gap. Project baselines and BIM action plan documents were studied to get an understanding of how 4D BIM is currently incorporated into the processes of Strukton Civiel. Besides, four of their projects were analysed as case studies to learn about the current application of 4D BIM in projects. By using the twelve 4D uses from the literature study as reference material, project members were interviewed to find reasons for applying these twelve uses. During this analysis, reasons were discovered which cannot be linked to specific 4D uses, but instead indicate if 4D BIM in general terms is feasible for the project. Furthermore, it was discovered that some 4D uses are applied as a configuration to decrease the combined effort of creating the 4D model. These configurations were evaluated by experts during an expert session. This session was also utilized to prioritize the most relevant and important 4D uses for Strukton Civiel at the time of analysis. Prioritization was done by plotting 4D uses on an impact versus effort matrix. Subsequently, this matrix was evaluated by experts and resulted in the six most relevant 4D uses.

In the design treatment phase, the information gathered in the previous phase was used to develop the assessment framework. This was subsequently adapted into a practical application in the form of a quick scan tool. To achieve this goal, requirements were specified and aspects were determined that make up the framework. This resulted in a framework that

should provide insight into the following three aspects or components: (1) beneficial 4D uses that suit the practical situation, (2) the feasibility or potential of 4D BIM in general terms, (3) configurations of 4D uses that are often applied together. The quick-scan tool is an example of the practical applicability of the assessment framework. It is designed to give project managers a first idea of whether or not 4D BIM is interesting and what the possibilities are in terms of 4D uses for different situations in practice. Different situations can be imitated with the questionnaire, where the answers lead to different outcomes of the three components.

The validation treatment of the quick-scan tool illustrated that experts generally thought that the tool is useful and that it adds value to projects. It was mentioned that the tool helps in engaging a discussion about the adoption of 4D BIM within the project. Moreover, it was indicated that the tool will be incorporated into the procedures of the company. However, it was also discovered that there is room for improvement. While the tool is capable of demonstrating the benefits of 4D BIM, insight into the implementation cost of developing the 4D model is desired. These costs have to be added to the result of the quick-scan in the future to balance out the assessment. Although this suggested the initiation of another design iteration, this research was limited to one iteration.

To conclude, this research developed a supportive tool for the decision-making process for adopting 4D BIM. The framework and the tool offer insight into whether or not 4D BIM is interesting for the project and, if so, what 4D uses are suitable for the situation in practice. Further research could focus on improving the assessment framework through another design iteration and by including the implementation costs of developing the 4D model. For Strukton Civiel and other practitioners, it is recommended to incorporate the quick-scan tool into the procedures of the company. Despite the limitations of the tool, it provides a solid starting point when deciding to make use of 4D BIM.

SAMENVATTING

4D Bouw Informatie Modeleren (BIM) associeert object-georiënteerde information van het bouwproject met tijd of planning gerelateerde informatie. Deze technologische ontwikkeling transformeerde de bouwindustrie gedurende de laatste 20 jaar en er zijn ondertussen diverse toepassingen van 4D BIM ontwikkeld die mogelijk van toegevoegde waarde zijn voor aan het project. Echter beschikken project managers over een beperkt budget en het implementeren van een 4D model kan geld en tijdrovend zijn. Of de voordelen opwegen tegen de kosten, is afhankelijk van de praktische situatie. Risico's met betrekking tot veiligheid, ontwerpfouten en uitloop op de planning zijn voor sommige projecten hoger dan andere. Bij projecten waarbij deze risico's hoog zijn, is de behoefte naar een 4D model mogelijk groter. Daarnaast, als blijkt dat 4D gewenst is, is het de vraag welke 4D toepassingen overwogen moeten worden. Deze afweging is onderdeel van het besluitvormingsproces van 4D BIM adoptie in ieder infra project van Strukton Civiel. Dit Nederlandse bouwbedrijf voert een breed scala van infra projecten uit en wil weten voor welke projecten 4D BIM interessant is.

Hoewel in de literatuur diverse toepassingen van 4D BIM worden behandeld, is er een kenniskloof betreft het linken van 4D BIM en bijhorende toepassingen met verschillende situaties in de praktijk. Het doel van dit onderzoek is daarom om deze kloof te dichten en bij te dragen aan de adoptie van 4D BIM door een afwegingskader te ontwikkelen dat het besluitvormingsproces van 4D BIM adoptie en bijbehorende toepassingen ondersteunt in verschillende praktische situaties. De ontwerpmethodologie van Wieringa (2014) is geraadpleegd om een methodiek te bedenken om het afwegingskader te ontwikkelen. De methodiek bestaat uit drie fases: probleemanalyse, ontwerpbehandeling en validatiebehandeling.

In de probleemanalyse fase is een theoretische en praktische studie uitgevoerd om te bepalen welke 4D toepassingen het meest relevant zijn voor infra projecten. Uit de literatuurstudie blijkt dat er twaalf 4D toepassingen voorkomen in de gehele levenscyclus van infra projecten. Echter is de literatuur beperkt als het gaat over de praktische situaties wanneer ze worden toepast. Daarom is er praktische informatie verzameld bij Strukton Civiel. Project baselines en BIM uitvoeringsplannen zijn bestudeerd om te begrijpen hoe BIM verankerd is in de processen van Strukton Civiel. Daarnaast zijn vier casestudies van verschillende regionale projecten van Strukton Civiel geanalyseerd om te bepalen hoe 4D BIM op dit moment wordt toegepast. Met de twaalf 4D toepassingen uit de literatuur als referentiemateriaal, zijn projectmedewerkers geïnterviewd om redenen te bepalen waarom deze twaalf toepassingen wel of niet worden toepast tijdens het project. Tevens zijn er redenen gevonden die niet gelinkt zijn aan specifieke 4D toepassingen, maar iets zeggen over de algemene haalbaarheid van 4D BIM. Andere bevindingen uit de casestudies suggereren dat een aantal 4D toepassingen veelal gezamenlijk worden toegepast als configuraties. Dit is omdat deze efficiënt in gezamenlijkheid kunnen worden toegepast. Deze configuraties zijn geëvalueerd door experts gedurende een expertsessie. Deze sessie is tevens gebruikt om de meest relevante en belangrijkste 4D toepassingen voor Strukton Civiel te prioriteren. Dit is gedaan door de 4D toepassingen te plotten op een impact versus effort matrix. Vervolgens is deze matrix geëvalueerd door experts en resulteerde in de zes meest relevante 4D toepassingen.

In de ontwerpbehandeling fase is het afwegingskader ontwikkeld op basis van de verzamelde informatie uit de vorige fase en is vervolgens omgezet tot een praktische applicatie in de vorm van een quick-scan tool. Om hiertoe te komen zijn eisen opgesteld en zijn de aspecten waaruit het kader bestaat bepaald. Dit resulteerde in een kader dat inzicht biedt in de volgende drie aspecten of componenten: (1) gunstige 4D toepassingen die passen bij het project, (2) de haalbaarheid of potentie van 4D BIM en (3) configuraties van 4D toepassingen die veelal gezamenlijk worden toegepast. De quick-scan tool is een voorbeeld van de praktische toepasbaarheid van het afwegingskader. Het is ontworpen om projectmanagers een eerste indruk te geven of 4D BIM wel of niet interessant is en wat de mogelijkheden zijn betreft 4D toepassingen voor verschillende praktische situaties. Verschillende situaties kunnen worden nagebootst door middel van de vragenlijst, waarbij de antwoorden leiden tot verschillende uitkomsten ten aanzien van de drie componenten.

De validatiebehandeling van de quick-scan tool illustreerde dat experts de tool veelal beschouwen als toegevoegde waarde voor projecten. Er werd aangegeven dat de tool ondersteuning biedt bij het discussiëren over de toepasbaarheid van 4D BIM binnen het project. Daarnaast werd aangeduid dat de tool verankerd wordt binnen de procedures van het bedrijf. Echter werd ook duidelijk dat er mogelijk ruimte tot verbetering is. Hoewel de tool inzicht biedt in de voordelen van 4D BIM, ontbrak er inzicht in de implementatiekosten nodig om het 4D model te ontwikkelen. Deze kosten dienen in de toekomst toegevoegd te worden aan het resultaat van de quick-scan om een balans op te maken. Ondanks dat dit een nieuwe ontwerpiteratie suggereert, is dit onderzoek beperkt tot één iteratie.

Concluderend heeft dit onderzoek een hulpmiddel ontwikkeld om het besluitvormingsproces van 4D BIM adoptie te ondersteunen. Het kader en de tool geven inzicht in de potentie van 4D BIM en mogelijke 4D toepassingen die aansluiten bij de praktische situatie. Vervolgonderzoek kan zich focussen op het verbeteren van het afwegingskader en de implementatiekosten toe te voegen door middel van een volgende ontwerpiteratie. Aan Stukton Civiel en andere bouwbedrijven wordt aangeraden om de quick-scan tool te verankeren in de procedures van het bedrijf. Ondanks de beperkingen van de tool, geeft het een degelijk startpunt als onderdeel van het besluitvormingsproces over 4D BIM.

TABEL OF CONTENT

LIST OF ABBREVIATIONS

BIM	Building Information Modelling
D&C contract	Design & Construct contract
GIS	Geo-Information Systems
LOD	Level Of Development[1]
MEAT	Most Economically Advantageous Tender
MEP	Mechanical, electrical and plumbing
O&M	Operation & Maintenance
PHS	Programma Hoogfrequent Spoorvervoer/Programme High-frequency Rail Transport
SBS	System Breakdown Structure
VBA	Visual Basic for Applications
WBS	Work Breakdown Structure

[1] Also known as Level Of Detail, but this research defines LOD as Level Of Development

1. INTRODUCTION

Ever since the exponential improvement of computing, the construction industry has seen a transformation where work processes are increasingly supported by digital technologies. One of the most dominant concepts that resulted from this transformation is Building Information Modelling (BIM) (Zhang et al., 2020). In the early stages of its emergence, traditional 2D drawings got transferred to 3D digital models to visualize and use the model on a digital platform. But the possibilities that BIM offered increased at a fast pace. One of these possibilities is 4D BIM, an active research topic for the last 20 years and is considered a useful addition to project management (Swallow & Zulu, 2019). 4D BIM adds the time dimension to the 3D model and offers a varying number of uses across the life-cycle of construction projects, for instance, 4D scheduling, 4D clash detection and 4D safety management. These applications provide new ways to collaborate and reduce design mistakes and increase productivity in the construction industry (Miettinen & Paavola, 2014).

However, the adoption rate of 4D BIM remains low (Boton et al. 2013; Nordahl & Merschbrock, 2016; Swallow & Zulu, 2019). Studies show that cost, time, and culture (including resistance to change) are the key barriers to causing a low adoption rate. (Swallow & Zulu, 2019). They recommend that research should be conducted on 4D BIM adoption to promote awareness of the benefits of 4D BIM. While there is research on different uses of 4D BIM, there is a knowledge gap on relating 4D BIM and associated beneficial 4D uses to different situations in practice. This includes the existence of a decision-making tool that indicates whether or not 4D BIM is interesting and what 4D uses are beneficial based on the different practical situations. Construction projects are characterized by their uniqueness in terms of their location, design specification and construction sequence of activities. As a result, it is different for each project whether or not the benefits that are offered by 4D BIM outweigh the required costs and time.

In an attempt to fill this knowledge gap, this study aims to contribute to 4D BIM adoption by designing an assessment framework that is adapted to different practical situations. This is designed using a design science methodology by Wieringa (2014) that describes the steps undertaken to design a framework. This framework is then adapted to a practical application, a quick-scan tool. This quick-scan provides a first impression of whether or not 4D BIM is interesting for a project and what 4D uses suit the practical situation. This study is done in cooperation with Strukton Civiel. This contactor is active within the Netherlands and has some experience with 4D BIM in infrastructure projects, but aims to increase 4D BIM adoption across all their firms in the Netherlands. Therefore, this was a good match for this research to obtain practical information on the subject and to contribute towards the common goal of the researcher and Strukton Civiel. In short, the objective of this research is defined as follows:

"To contribute to 4D BIM adoption by designing an assessment framework that supports the decision-making process for adopting 4D BIM and its most relevant 4D uses in different practical situations"

This report is structured as follows. In chapter 1, more background on 4D BIM is provided using available literature and the problem is described in more detail. Besides, research questions are defined based on the problem definition and research objective. In chapter 2, the research methodology is described how the research questions are answered. In chapter 3, an overview is given of the 4D uses that were discovered during the literature study. In chapter 4, an analysis is made of the current situation regarding 4D usage at Strukton Civiel. In chapter 5 the design treatment of the assessment framework is described in addition to the quick-scan tool. Then in chapter 6, the developed quick-scan tool is verified and validated. Finally, a discussion and conclusion are made regarding the results of this research in chapters 7 and 8 respectively.

1.1. Theoretical Background

While this research is focused on 4D BIM, more context about BIM is required, since the 4D technology is part of BIM. This context is based on a preliminary literature study. Firstly, the definition of BIM assumed for this research is explained and its use is put into the context of the infrastructure sector. Secondly, recent research efforts are described and 4D is explained in more detail in terms of 4D BIM uses and the reasons for the slow adoption rate.

1.1.1. Definition of BIM

The concept of BIM is rather ambiguous and understood differently. According to the influential *BIM Handbook* by Eastman et al. (2017) and a study by Miettinen and Paavola (2014), BIM is a popular buzzword used by software vendors to describe the capabilities that their products offer. This results in variations and confusion in the definition of the concept. A worldwide commonly accepted definition by the US National Building Information Model Standard Project Committee provides a sufficient understanding:

"Building Information Modelling (BIM) is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition" (NBIMS-US, 2016).

This definition is dissected to get a better grip on what BIM entails. In this definition *digital representation of physical and functional characteristics* refers to the 3D building model consisting of objects that carry computable graphic and data attributes (Eastman et al., 2017). However, BIM is much more than just a 3D model as it could also be used as a *shared knowledge resource of information.* This implies the ability for multiple disciplines with a different role (project manager, architect, structural engineer, MEP engineer) to work on a centrally shared model in a coordinated sense. A *reliable basis for decisions* refers to BIM assisting in the decision-making process by combining different sources of information, for instance using quantity take-off to determine the number of resources required to complete a project. The *life-cycle* integration allows data to be useful from the start of the project until the product has reached its end of life. This is important because the use of BIM is dependent on the project stages, which is described in the following subsection.

1.1.2. Life-cycle for infrastructure products

BIM can be adopted at various stages of the product life-cycle, which is why it is important to shortly clarify what a product life-cycle implies. In principle, the life-cycle of any product is the period in which it is in existence, either conceptually or physically (Murthy & Jack, 2014). However, the stages the life-cycle goes through depends on the chosen perspective and the product. From the perspective of infrastructure product owners, the product life-cycle is the time between initiation of the process until discarding or upgrading the product (Murthy & Jack, 2014). This including the stages in between as shown in Figure 1.

Figure 1: Life-cycle of infrastructure products from the perspective of the project owner(Murthy & Jack, 2014)

Based on the study by Murthy & Jack (2014), the following can be mentioned about the stages as seen in Figure 1:

1. Initiate: The idea for a new or updated product emerges and is evaluated in terms of feasibility and desired characteristics. The result of the evaluation is either a go or a no-go (Ben-Daya et al., 2016). Depending on the contract, builders could at this stage be invited to tender;
2. Design: In this stage, the project needs are translated to a design. Various disciplines cooperate as the design team to create a cohesive design. This evolves from conceptual design to a detailed design;
3. Develop: Pre-construction stage where everything that is required to execute the project is arranged. Among these activities are scheduling, budgeting and the allocation of other specific tasks and resources;
4. Built: The project plan is put into motion by the builder and the work on-site is performed. During this stage, control is maintained as needed;
5. Deliver: Post-construction stage where most of the commissioning activities are completed. This includes inspections to check if the product is in line with the requirements and documenting whether the project was finished within time and budget;
6. Operate and maintain (O&M): Well-defined, tested and verified procedures that are made available by the manufacturer. O&M strategies can be developed in-house by the owner itself or can be outsourced to an external party (Ben-Daya et al., 2016);
7. Discard or upgrade: At the end of the product's intended life-cycle, the owner has to decide whether to discard the product or to extend its life-cycle by improving the quality.

The life-cycle for infrastructure product builders is different, as the entrance in the product life-cycle as shown in Figure 1 depends on the contract (Murthy & Jack, 2014). The owner specifies the initial requirements of the project and then the final requirements are negotiated jointly with the builder in a contract. In the case of an integrated contract (Design & Construct or Design, Build, Finance, Maintain & Operate), the builder could be involved from as soon as the *design stage* until the *O&M stage*. In a more traditional, the owner is responsible for the design and hands it over to the builders. When construction is finished, the builder delivers the infrastructure product to the owner and the responsibility shifts to the owner for the remainder of the life-cycle.

What this means for the use of BIM is that the added value depends on the perspective taken from the life-cycle and on the contract type. In a traditional contract, the builder might be reluctant to develop a BIM because the benefits are limited compared to its implementation costs (Sloot, 2018). In an integrated contract there might be more incentives for the builder to develop a BIM when they are responsible for the infrastructure product for a longer duration in the life-cycle, thus the builder can exploit its benefits more extensively (Sloot, 2018).

The next subsection provides more information on BIM in the infrastructure sector and compares BIM in the infrastructure sector with BIM in the building sector.

1.1.3. BIM in the infrastructure versus building sector

This study focuses on the infrastructure sector, while most research surrounding BIM is focused on the building sector (Bradley et al., 2016). Although both sectors share many similarities in terms of BIM usage, certain differences are also discovered. According to Bradley et al. (2016), both sectors use BIM in the design review process, as a collaboration methodology, and to some extent the coordination of the works. These authors state that the main difference is in terms of where the advantages are fully embraced. Buildings are heavily component-based, implying fixed geometrical shapes such as windows, ventilation ducts and doors. Therefore, clash detection is considered very useful in determining conflicts between components that make up the built asset at an early stage of the project. Another advantage of BIM is the technical aspects so the clarity of information and visual aids during the design stage. In infrastructure projects, such as a highway project, the modelling is less component-based. Therefore, clash detection is less interesting compared to the application in the building sector. Advantages are usually present in terms of coordination and visual integration of non-graphical data into the model during the pre-construction and construction stage (Bradley et al., 2016). Non-graphical data includes information such as manufacturer, cost estimations and material information. However, BIM is also useful further along the life-cycle of infrastructure projects. The information model can be transferred to operating agents that can integrate the model into their network dataset. However, as for all BIM approaches, the usefulness of the model is dependent on the capability of all participating parties in the life-cycle to make use of the model (Bradley et al., 2016).

To sum up, the sector could influence how BIM is used in practice. Actual applications of BIM are described in the next subsection.

1.1.4. BIM applications

Now that BIM has been defined and distinguished from the infrastructure perspective, a closer look can be given to what possibilities BIM has to offer. BIM applications other than 3D BIM include more than 3 dimensions and are often referred to as nD-modelling. 4D BIM adds the time dimension and offers mainly benefits in the pre-construction and the construction stages. While the adoption of 4D technologies has been circulating since 2000, new types are still in development. 5D BIM incorporates costs expressed in terms of materials used or costs required for assembly. 6D BIM and beyond could include aspects of building performance, such as sustainability, energy, safety and acoustic (Koutamanis, 2020). Other recent efforts in research have been made to integrate Geo-Information Systems (GIS) with BIM, especially studies focusing on the infrastructure sector (Bradley et al., 2016). GIS gives the participants the ability to store, manage and analyse data describing the urban environment. Possible applications of GIS include cost estimates to identify options and solutions for materials layout problems (Irizarry et al., 2013). BIM and GIS as an integrated solution combine information of the building with information from the urban surroundings. For instance, Irizarry et al. (2013)

developed an integrated BIM and GIS model to visually monitor the supply chain management by tracking the supply chain status and warning the user to ensure the delivery of materials. While the recent development of nD modelling beyond 4D is not within the primary scope of this research, certain elements might be features of 4D BIM.

The next section describes examples from literature on how 4D BIM is used.

1.1.5. Using 4D BIM

As previously mentioned, 4D BIM associates elements of the 3D model with time. While its use is most often linked to planning purposes, there are a variety of other uses. The main benefit of 4D is the visualization aspect as well as information accessibility, the capability to share the knowledge resources minimizes the need to re-gather and re-format information (Umar et al., 2015). There are various uses or applications of 4D BIM, of which the following will shortly be described to get an idea of what 4D offers:

- 4D team communication is used to forecast construction and demolition stages and the sequence of activities. Compared to other paper-based schedules, as bar chart schedules, 4D scheduling provides provide a more complete and consistent overview (Nordahl & Merschbrock, 2016). As such, it allows for visualization of the building design progression. It also produces meaningful information for the project team, like the start and finishing dates of elements as well as their criticality (activities that cause discontinuity of activities on the longest path) (Umar et al., 2015).
- 4D safety management allows for better detection and anticipation of potential safety issues with equipment, for instance, conflicts of a moving tower crane with workers or pedestrians (Guerriero et al., 2018).
- 4D clash detection provides a spatial-temporal addition to 3D clash detection. While clash detection is already applicable with a 3D model, 4D adds the possibility to resolve conflicts that can be both static and dynamic and occur during construction (Guerriero et al., 2018).
- 4D point clouds are used to monitoring work-in-progress using laser scanning or image-based point clouds. This is done to compare the as-built information against the as-planned model to look for any deviations (Han et al., 2015).

These are just examples of 4D BIM uses and part of this research focuses on more uses. Also, some uses might prove to be irrelevant as they could have insignificant added value or require too much time to develop. What 4D uses should be used in a project and how much work time investment is required, depends on the project life-cycle stage and project characteristics. Some projects benefit from the integration of various 4D uses into many processes of the project life-cycle, which could require much effort to develop the 4D model (Boton et al., 2015). Other projects might find it useful to have just a 4D animation for visual communication with other stakeholders, which could require little effort to develop the 4D model. Furthermore, information included in the models can be developed with a low or high amount of detail, depending on project and business needs (Boton et al, 2015). It is important to know that information accessibility develops over time. In the early project development stages, the available information is limited. As the project progresses more information becomes available. To incorporate the difference in the quantity of information, the BIM model is often divided into a different level of development (LOD) (Butkovic et al., 2019). LOD concerns the quantity of (non) graphical information that is added to the model for each stage of the project to serve its function (Eastman et al., 2017). The level of development is not the same as the level of detail. The main difference is that the level of development includes non-graphical information, such as construction activities schedules, whereas the level of detail only concerns geometry. Therefore, the level of development is more commonly used when discussing 4D BIM. According to Solihin & Eastman (2015), these are the six commonly used LOD levels:

- LOD 100: only objects in graphical representation;
- LOD 200: addition of quantities, shape, location and orientation with possibly non-graphic information;
- LOD 300: more specific systems, objects;
- LOD 350: addition of requirements on interfaces with other building systems;
- LOD 400: more detailed information required for fabrication, assembly and installation;
- LOD 500: as-built representation and incorporates information about operations and maintenance.

The required LOD that is added to a 4D model varies per 4D use. Usually, both a low LOD or high LOD is possible with 4D uses. For instance, 4D visual communication could be both, since a 4D animation could be made with a conceptual model and with a model that includes information about installations. 4D monitoring with point clouds is usually done with a high as-built LOD 500, but a study by Han et al. (2015) shows that a low LOD is also possible where operation data is omitted.

Now that it is known what some applications of 4D BIM are, the next subsection provides insight on what hindered the widespread adoption of 4D BIM.

1.1.6. Adoption rate of 4D BIM

Although there are many 4D uses with proven benefits, the adoption rate of 4D BIM in the construction industry remains low (Boton et al., 2013; Nordahl & Merschbrock, 2016; Swallow & Zulu, 2019). In this context, the adoption of 4D BIM refers to the implementation of the object and time-based modelling tools and workflows.

Several studies try to find reasons for the low adoption rate. The study of Boton et al. (2013) explains that while the technology is increasingly used in wide-scale or specific engineering projects, it is still considered a young technology that has to be adapted to business needs. According to Nordahl & Merschbrock (2016), the use of 4D BIM is impractical and difficult to use in everyday construction operations. Structure, culture, and routines for 4D BIM are required for this technology to serve its intended purpose of improving construction processes (Nordahl & Merschbrock, 2016). A study by Swallow & Zulu (2019) also acknowledges culture as a barrier and argues that while this barrier is difficult to overcome, efforts for change need to be made to allow the industry to adapt to the new ways of working. Other key barriers to 4D BIM adoption mentioned by these authors are time and financial investment. Mahalingam et al. (2010) describe barriers like these as organizational and project-specific that hinder the widespread adoption of 4D BIM.

In short, 4D BIM could improve construction processes but there are organisational and situational-specific barriers that cause practitioners to dismiss the adoption of 4D BIM. This leads to the problem definition in the next subsection.

1.2. Problem statement

From the preliminary literature review can be concluded that there are several uses of 4D BIM along the life-cycle of infrastructure project, but that there is a knowledge gap in terms of the practical situations in which 4D BIM is interesting and what 4D uses are fitting for different situations. Authors (Nordahl & Merschbrock, 2016; Swallow & Zulu, 2019; Mahalingam et al., 2010) recommend researching the current adoption of 4D BIM and making an effort to overcome organizational and project-specific barriers. In addition, it is recommended to investigate the feasibility for further investment in 4D modelling within projects and to increase the awareness of the benefits of 4D BIM (Swallow & Zulu, 2019). This scientific problem shares similarities with the problem currently presenting itself at Strukton Civiel. The contractor carries out a wide range of projects which differ in complexity, costs and contract type. The benefits that are gained from using 4D BIM are for some projects outweighed by the cost and time investments. For instance, for a small project with a traditional contract where the client is responsible for the design, the need to develop a 4D BIM model is limited. For other projects, the use of 4D BIM might be more attractive. In the case of a high-risk Design & Construct (D&C) project where Strukton Civiel is responsible for the design, they can prevent failure costs in the early stages of the project using 4D BIM. Moreover, the affinity with 4D is different for each operating region. While Strukton Civiel Projecten has experience with 4D BIM, some firms from Strukton Civiel have just recently incorporated 3D BIM in their working methods and are still inexperienced with 4D BIM. The expansion of 4D BIM usage throughout all firms is slow due to several reasons. Firms are spread throughout the country and there are few communication moments where BIM usage is discussed. Also, the benefits of 4D BIM are unknown to some project managers and are therefore reluctant to experiment with 4D BIM. In short, the problem can best be described using the following problem statement:

"There is a knowledge gap in terms of whether or not 4D BIM is interesting for infrastructure projects in different practical situations, and if so, what 4D uses are beneficial in these situations."

1.2.1. Research objective

On account of the problem definition can be determined how the planned research should contribute to solving the problem. While there is literature available that focussing on 4D BIM adoption and 4D uses in infrastructure projects, there is no research on 4D BIM and 4D uses linked to different situations in practice. This research attempts to fill this knowledge gap and contribute to 4D BIM adoption by designing an assessment framework. The framework is used as input to develop a quick-scan tool that offers project managers a practical approach in the decision-making process for adopting 4D BIM. This tool should provide project managers with a first impression of whether or not 4D BIM is interesting for their project and what 4D uses suit the practical situation.

To achieve this objective it is first important to understand what 4D uses can be distinguished across the entire life-cycle of infrastructure projects. Then is figured out how 4D is applied in practice, what reasons are for applying 4D uses, what project characteristics influence the use of 4D and what 4D uses are considered as the most relevant. All this gathered information provides the groundwork for designing the assessment framework and ultimately adapting this framework into the quick-scan tool. As previously mentioned in the introduction of this research, the main research objective is defined as follows:

“To contribute to 4D BIM adoption by designing an assessment framework that supports the decision-making process for adopting 4D BIM and its most relevant 4D uses in different practical situations.”

1.2.2. Research questions

Based on the defined problem statement and the objective, the research questions can be composed. The main research question is as follows:

“What does an assessment framework look like that supports the decision-making process for adopting 4D BIM and its most relevant 4D uses in different practical situations?”

The following central research question and complementary sub-questions answer the main research questions in a structured manner:

1. What 4D uses can be distinguished across the entire life-cycle of infrastructure projects that are most relevant for Strukton Civiel?
    a. What 4D uses across the entire life-cycle of infrastructure projects can be distinguished in literature?
    b. What 4D uses are currently applied at Strukton Civiel and why are they applied?
    c. What are the processes surrounding the use of 4D BIM at Strukton Civiel?
    d. What project characteristics can be distinguished that influence the use of 4D BIM?
    e. Which of the 4D uses as found in the literature are most relevant for Strukton Civiel?

   The purpose of these questions is to get a fundamental understanding of the theoretical and practical side of 4D BIM. This is important to ultimately filter the 4D uses that are most relevant for Strukton Civiel. The 4D uses result from a literature study. These 4D uses are utilized as reference material in a practical study at Strukton Civiel. This practical study also results in processes that support 4D BIM and project characteristics (such as complexity, size and contract type). Ultimately, all information is used to provide the most relevant 4D uses.

2. What are the requirements for the assessment framework?
    a. What the requirements from Strukton Civiel for the assessment framework?
    b. What are the aspects that make up the assessment framework?

   The answer to these questions should provide the means to develop the assessment framework that is in line with the business needs of Strukton Civiel. The reason to develop requirements is to establish the structure of the assessment framework in advance and to design a product that is more likely to be useful. Besides, the specification of requirements implies that the product can be verified once the design is completed.

3. What is the relationship between 4D BIM, its most relevant 4D uses and different practical situations?

   a. What relationship can be made between 4D BIM and different practical situations?
   b. What relationship can be made between the most relevant 4D uses and different practical situations?

   The purpose of these questions is to make the aspects of the assessment framework project-specific for different practical situations. This is researched in terms of 4D BIM in general and its most relevant 4D uses. Together both relationships result in the assessment framework. This information can then be used to design the practical adaptation, the quick-scan tool.

4. What does the verification and validation of the quick-scan tool tell us about the usefulness and added value of the designed tool?
   a. Does the quick-scan tool satisfy the specified requirements?
   b. What are the usefulness and added value of the quick-scan tool based on the opinion of experts that have used the framework in the project context?

   This question determines to what extent the quick-scan tool is useful to Strukton Civiel. First, the requirements previously specified are verified to determine if the quick-scan tool satisfies the requirements. Secondly, by asking employees from Strukton Civiel to use the quick-scan tool in the decision-making of using 4D BIM, the product can be tested in a project environment. Then, by asking the employees to give their feedback, the quick-scan tool is validated.

2. METHODOLOGY

The described problem of this study can be classified as a practical problem. To develop a solution, the study calls for a design methodology. Wieringa (2014) proposed an engineering cycle with the steps required to design a solution and is suited to an artefact like an assessment framework. The engineering cycle consists of four phases: (1) problem investigation, (2) treatment design, (3) treatment validation and (4) treatment implementation. Figure 2 shows these steps in addition to the intermediate steps, where the question marks indicate knowledge questions, and the exclamation marks indicate design problems (Wieringa, 2014). For this research, only a part of the engineering cycle, namely the design cycle is implemented. The design cycle does not include the final implementation phase of the engineering cycle. This is because Strukton Civiel is responsible for complete implementation based on their perceived usefulness.

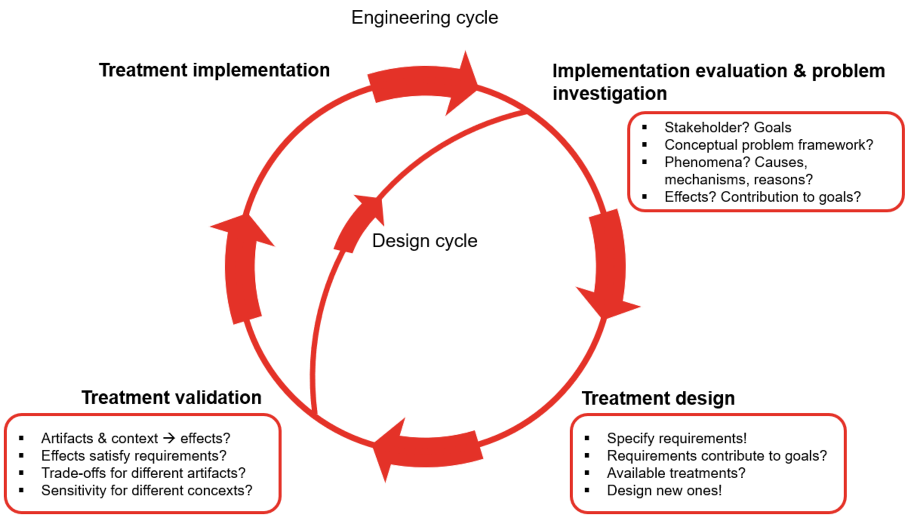


Figure 2: Empirical cycle (adaptation from Wieringa, 2014)

In this chapter, a research design is provided that describes the research methods used to collect the data necessary to answer each of the research questions. Figure 3 provides an overview of the research design, where the phases are based on the steps of the design cycle as developed by Wieringa (2014). In addition, the methodology described by Verschuren & Doorewaard (2010) was consulted to design this research.

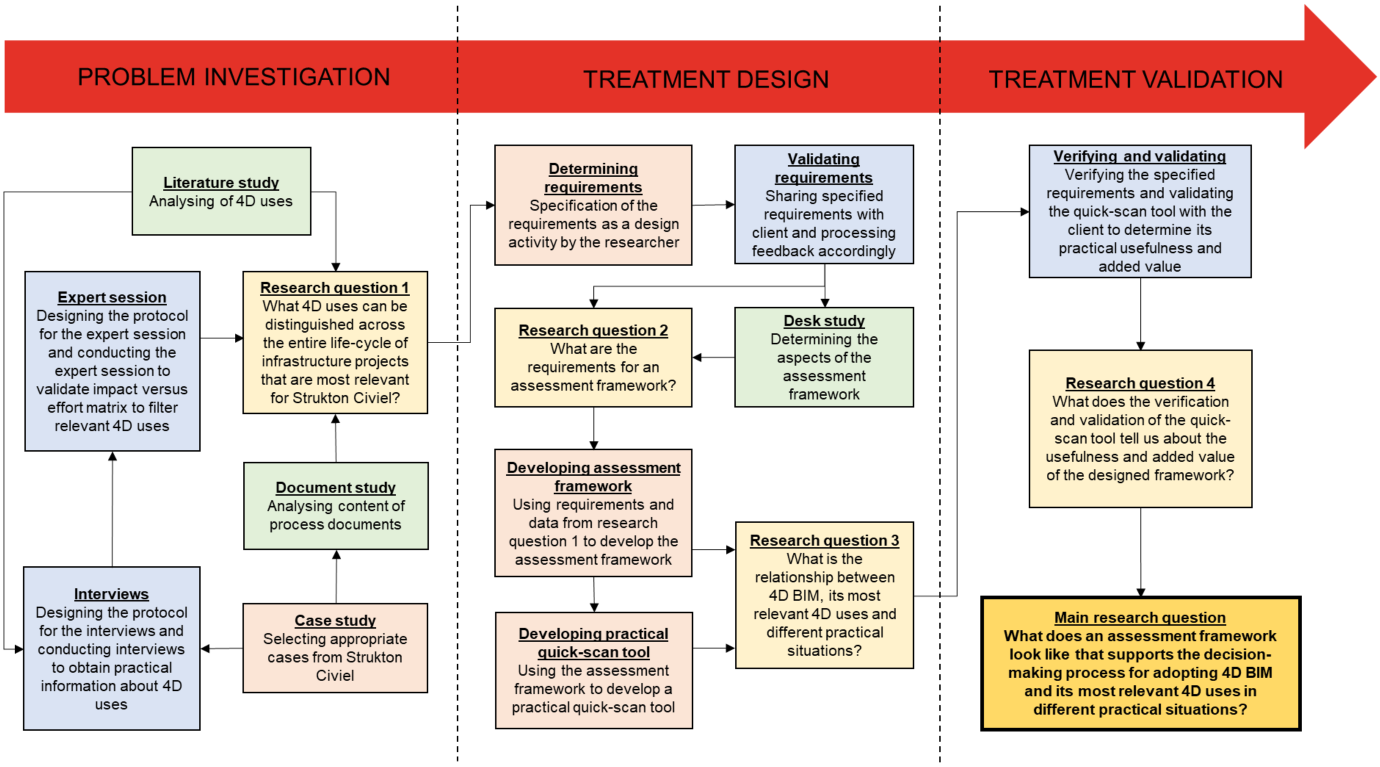


Figure 3: Research design

2.1. Problem investigation

In this phase, 4D BIM was explored in-depth with regards to the most relevant 4D uses for Strukton Civiel. This provided the answer to research question 1. To achieve this, literature was consulted and case studies were analysed to get a thorough understanding of 4D BIM uses in theory and practice. Subsequently, an expert session was held to determine which 4D uses are more relevant for Strukton Civiel at the moment.

The literature study concerned gathering information from literature about all the 4D BIM uses across the life-cycle of infrastructure projects. This provided the necessary information to set up the first round of interviews as part of the case studies. In addition, it provided a set of literature articles that were referred to in the development of the framework. These articles were found by using the following keywords and Boolean operations: *(4D BIM OR 4D uses) AND (infrastructure OR construction).* Database sources such as ScienceDirect and Google Scholar were consulted for the literature study.

The case studies concerned analysing information about how and why 4D BIM is applied and carried out in practice. This information was vital input for the framework at the treatment design phase. The reason for conducting case studies was because qualitative research was preferred and also partly because carrying out an in-depth study was required to understand the underlying processes and the project characteristics that result in certain 4D uses. The selection of the cases was based on a strategy by Verschuren & Doorewaard (2010). These authors mentioned case selection could be based on cases that show several differences in certain aspects and are similar in the remaining aspects. Taking this into consideration, the selection of the case studies was made based on the following aspects. Firstly, there was a difference in the project size. This ranged from projects between 30 and 110 million euros. Secondly, there was a difference in terms of complexity and uniqueness. Thirdly, there was a difference in the extent to which BIM was used. Strukton Civiel did not make use of 4D BIM extensively. There were just a few projects where 4D has been applied. These projects were considered in the analysis. Since this amount was fairly low, the decision has been made to also include projects which adopted 4D at a small scale. Finally, the project was executed by different regional firms of Strukton Civiel. This provided a broader understanding of BIM adoption for firms with different levels of experience with 4D BIM.

The case study projects analysed for this research are presented in Table 1. It would have been interesting to consider projects with different contract types other than D&C. However, BIM was at the time only applied in projects with design & construct contracts. Therefore, projects without a D&C contract were not selected for the case study analysis. 2

Case #	Project	Regional firm	Interviewee #	Role
1	Tender N307 Roggebot	Strukton Civiel Noord & Oost	1	Technical manager
		Sweco	2	External BIM modeller
2	PHS Rijswijk - Delft	Stukton Civiel Projecten	3	BIM coordinator
3	Groningen Central Station	Strukton Civiel Projecten	4	BIM director
		Strukton Civiel Projecten	5	Work planner
4	Reopening of the Roode Vaart and reconstructing the market in the centrum of Zevenbergen	Strukton Civiel Zuid	6	Project manager

Table 1: Overview of case study projects selected for this research

Data about the case studies were gathered by using document and interviews analysis. Firstly, the document study was conducted to understand the underlying processes of applying 4D BIM. This was important to determine at which project stages certain 4D uses could offer value. This qualitative method consisted of extracting information from a selection of relevant textual material (Verschuren & Doorewaard, 2010). Secondly, the interviews were conducted to gather information about the 4D BIM uses that are currently applied at Strukton Civiel. There are multiple ways to conduct an interview: unstructured interviews and (semi) structured interviews. Unstructured interviews make use of a list of subjects that were discussed. Structured interviews make use of a prepared questionnaire. Semi-structured interviews are a more flexible variant. Similar to structured interviews, the interview followed a list of prepared questions, but the questioner can deviate from the list to obtain deepened information. The interviews were mostly conducted preferably face-to-face to see the body language, but when the COVID-19 circumstances did not allow this, they were done using digital videoconferences. These respondents were employees working at different locations to get a national comprehension of using 4D BIM, as can be seen in Table 1. The group of employees consisted of various had affinity with the use of 4D BIM and the sample includes BIM managers, project managers and site managers. With the permission of every respondent, the interviews were recorded to write case projects of the most important findings. The questions used in these interviews together with the most important findings per case are reported in Appendix B. After conducting the interviews, it was discovered that additional interviews were necessary because of white spots in terms of the reasons certain 4D uses were applied. This was because the initial interviews did not directly refer to the 4D uses discovered in the literature.

After completing the case studies, the collected information was used to determine the 4D uses that were most relevant for Strukton Civiel at the time of analysis. This prioritization was done by plotting 4D uses in an impact versus effort matrix. The case studies provided the researcher with an idea of what currently the most important uses are. Since this was an activity of the researcher, the matrix was evaluated with expert opinion to increase its validity. This opinion was obtained during an expert session with four experts. These experts had been previously interviewed and were familiar with the research. Besides, the group of experts was a heterogeneous mix of two project managers and two BIM managers. Since one of the experts could not attend the session, a second session was held with this individual. The complete protocol and results of the expert session are provided in Appendix C. After comparing the scoring of the 4D uses, a conclusion was made on what 4D BIM uses are most relevant for Strukton Civiel at the time of analysis.

The next step was to develop the requirements for designing the assessment framework, after which the framework was developed.

2.2. Treatment design

In this phase, the assessment framework was developed and research questions 2 and 3 were answered. To answer research question 2 requirements were specified and the aspects of the assessment framework were structured. According to Wieringa (2014), the client often has a hard time specifying requirements and it is rather a design activity of the design researcher. Therefore, the specification of the requirements from Strukton Civiel was a joint process. The researcher specified requirements and motivated its decision based on contribution arguments. This argument is a prediction that the requirement contributes to a stakeholder's goal in the problem context (Wieringa, 2014). The requirements were then shared with the experts from Strukton Civiel and were then adjusted based on the feedback. Besides the specification of requirements, desk research was conducted to find the aspects that make up the assessment framework. This was based on information from literature or policy documents. Together they provided the means to develop the framework.

The next step in the treatment design was to translate the requirements into the assessment framework and answer research question 3. The researcher had already determined reasons to (not) apply 4D BIM and its associated uses by using case study findings. Besides, articles were gathered during the literature study that provided more reasons to apply 4D uses. In addition, project characteristics have been identified that influence the use of 4D BIM. Combining all this information, conditions under which 4D BIM and its associated uses are applied were determined, which was the groundwork of the assessment framework. The intermediate steps are provided in Appendix D. Next to these conditions, the framework describes combinations of 4D uses that go hand in hand. Determining the combinations or configurations was an iterative process based on three steps. Firstly, the researcher looked for clusters of 4D uses that were related to one another based on the conducted case studies. Secondly, these clusters were evaluated by experts during the expert session. Thirdly, the configurations are adjusted where necessary based on the results of the session. Also, the results of the impact versus effort matrix were incorporated in this step. The intermediate steps are given provided in Appendix C.3, including the results per expert from the expert session.

Then by using the framework as input, a practical quick-scan tool was created. This tool should not be considered as a highly detailed tool that calculates implementation costs or provides instruction on how 4D should be implemented. Instead, the tool should help in deciding whether or not 4D is interesting. This was done by translating the conditions into questions. These questions were linked to either 4D BIM feasibility or 4D uses.

With the assessment framework complete, the final phase of this study was verifying and validating the framework.

2.3. Treatment validation

In the final phase, the quick-scan tool was verified and validated and provided the answer to research question 4. Verification was done by checking if the specified requirements were met. Validation was done to determine if the quick-scan tool satisfied the needs of the client and if the quick-scan is considered useful. The group of employees consisted of four future users/experts (project leader, planning department manager, BIM director and head of project management) from Strukton Civiel. This group was involved with the research project throughout the research period and are future users of the tool. They were asked to use the quick-scan tool in the decision-making process of using 4D BIM for a project currently in progress or a hypothetical project. After using the quick-scan tool in the project context, they were asked to answer a set of questions. The questions were closed-ended (with the option to comment) and are provided in Appendix F together with the answers given. Their feedback could have been used to initiate another cycle of the design cycle. However, to limit the scope of this research the design cycle was only performed once. With the treatment validation, insight was provided into the practical usefulness and added value of the quick-scan tool.

After the quick-scan tool had been validated, the design cycle was completed and a conclusion was provided on the results of this research.

3. 4D BIM IN LITERATURE

This chapter aims to provide an analysis of 4D uses in the construction industry to ultimately determine the most relevant 4D uses for Strukton Civiel. With this information, it is possible to partially answer the first research question. This was completed with a systematic literature review. These uses were used as reference material in the practical part of this study.

The result of the literature search is given in Table 2, which provides an overview and description of all the 4D uses discovered. In total, twelve uses were found that make use of the 4D aspect.

#	4D use	Description	Publication(s)
U1	Stakeholder communication with the 4D model	Communicating to stakeholders (external parties, such as the client and the public) using a 4D model of the project schedule and/or the spatial location of work tasks. This is useful to help them understand the complexities involved and the steps required to complete the project	Bolshakova et al. (2018), Hartmann et al. (2007), Khwaja & Schmeits (2014)
U2	Team communication with the 4D model	Communicating to team members (internal parties such as the project team and subcontractors) by using the 4D model about the construction and demolition phases and the sequence of activities. Off-site, the 4D model can be used to understand the design faster and discuss the ideas to optimize the schedule. On-site, the 4D model can be used for daily/weekly/monthly team meetings where the coming activities are discussed. In addition, the model can be used to assess as-built with as-planned schedules	Bolshakova et al. (2018), Hartmann et al. (2007), Umar et al. (2015)
U3	4D clash detection	Discovering conflicts caused by lack of coordination in the different designs of co-builders, construction schedule sequencing and planned construction operations	Bolshakova et al. (2018), Trebbe et al. (2015)
U4	4D site layout	Creating an integrated site layout system with management, visualization, schedule and facility layout across the dynamic 3D site. This integrated system can be used to plan the construction phasing	Bolshakova et al. (2018), Gledson & Greenwood (2016), Ma et al. (2005)
U5	4D site layout with temporary works	Making a more realistic construction site coordination plan by visualizing temporary structures (i.e. scaffolding, excavation support and falseworks) and associated safety hazards into the BIM and planning	Gledson & Greenwood (2016), Kim & Cho (2015), McKinney & Fischer (1998)
U6	4D constructability management	Using 4D visualization as a project management technique for reviewing construction processes from start to finish during the pre-construction stages. Alternative construction sequence could be simulated to evaluate the overall constructability of the design	Bolshakova et al. (2018), Hartmann et al. (2007)
U7	4D progress monitoring with point cloud scanning	Monitoring work-in-progress using laser scanning or image-based point cloud. This is done to compare the as-built information against the as-planned model to look for any deviations	Bolshakova et al. (2018), Han et al. (2015), Kim et al. (2013)

U8	4D safety management	The visualization of the design could be used to identify possible (working-at-height) hazards and advising all project participants with prevention measures using the visualization of the design. Since the risk of injury varies per activity, safety should be managed from the perspective of both time and space	Benjaoran & Bhokha (2010), Ding et al. (2014), Choe & Leite (2017), Guerriero et al. (2018)
U9	Concrete pouring schedule and construction joint layout with 4D BIM	Creating realistic concrete pouring designs, schedules and work orders. This could be done with a 4D BIM approach to facilitate automated concrete joint positioning solutions	Sheikhkhoshkar et al. (2019)
U10	4D maintenance tasks	Supporting real-time maintenance tasks with the use of inspection records, maintenance schedules and costs, and degradation models	Hallberg & Tarandi (2011), Zhang et al. (2018)
U11	Quality control with 4D BIM	Combining model with the inspection data of execution activities, such as high-pressure jet grouting, for quality control	Chen et al. (2014), Ding et al. (2014)
U12	Option evaluation of decommissioning alternatives with 4D BIM	Visualizing different decommissioning options at the end of a structure's life-cycle with 4D simulation applications to have a good understanding of each option and subsequently, choose the most feasible option	Cheng et al. (2017)

Table 2: Overview of 4D uses found in the literature

As can be noted from Table 2, a large number of 4D uses has been researched in other studies. While most uses have a different purpose, the common denominator is the inclusion of time-based information. Some other similarities between certain uses are also worth mentioning. Firstly, using 4D to plan or to schedule is embodied in several 4D uses. Creating a 4D site layout, possibly including the temporary works, can be used to plan the construction phasing sequence. Concrete pouring schedule and construction joint layout with 4D BIM can be used to automatically create a planning of the concrete volumes required to build the structure.

Secondly, stakeholder and team communication both concern using the 4D model as a communication tool to, for instance, make the complex design easier to understand. However, they are kept as separate uses. The main difference is the group of individuals to which the model is showcased. For stakeholders, the visualization is mainly an effective way to communicate engineering issues to non-engineers, whereas for teams the visualization is mainly used by engineers to discuss their idea (Hartmann et al., 2007). In this research, stakeholders are understood as external parties, such as the client and the public. The team is understood as internal parties, such as the project team and involved sub-contractors.

Thirdly, 4D site layout and 4D site layout with temporary works are similar, but the temporary construction works add a level of realism to the 4D site layout (Kim & Cho, 2015). Temporary works or supports (scaffolding, excavation support and falseworks) refer to additional support for building components at the time of installation. They are often dependent on the construction method chosen by the contractor and are typically not represented in a 3D or 4D model of the structure (McKinney & Fischer, 1998).

In this chapter, a list of twelve 4D uses was determined using a literature study. At this moment it is unknown which uses are more relevant than the others. In addition, it is unclear in which practical situations they could be applied. Literature research is limited on this matter and, therefore, practical information is gathered on this subject.

4. 4D BIM IN PRACTICE

This chapter provides an analysis of 4D BIM use in practice. Its purpose is to provide the answer to research question 1: what 4D uses can be distinguished across the entire life-cycle of infrastructure projects that are most relevant for Strukton Civiel?

The chapter is structured in three sections. Firstly, the document study has provided relevant background information on the underlying processes according to the project life-cycle stages followed by Strukton Civiel. Secondly, four case studies have been analysed to determine the 4D uses currently applied at Strukton Civiel and to identify the project characteristics that influence the use of 4D BIM. Finally, the 4D uses are distinguished in terms of configurations that are most relevant for Strukton Civiel.

4.1. Document study on the BIM processes across the project life-cycle

This section elaborates on the BIM processes embedded into the project life-cycle stages adopted by Strukton Civiel. This step is important to understand the distinction between the project stages and how 4D BIM is embedded into these stages. Data used to answer the question is derived from documents from Strukton Civiel. These documents describe the project baseline and BIM execution plans. The project baseline is described to understand the approaches and processes behind every design and construct project. BIM execution plans are described to understand the agreements made with the project team and project partners in terms of BIM use.

In subsection 1.1.2 the general life-cycle stages found in the literature were defined from the perspective of the product owner (client) and the builder (contractor). While Stukton Civiel follows a fairly similar life-cycle approach, theirs is more comprehensive and detailed. The baseline is split up into two main parts that follow the course of the project: tendering projects and realizing projects (Strukton Civiel, 2020)[1]. Subsection 4.1.1. and 4.1.2. describe the steps and stages for both acquisition and realization. Noteworthy is the fact that all the steps in the processes are advised, but not obligatory. They serve as a checklist of the steps included in managing a construction project, in this case, projects with an integrated contract (D&C). In the following subsection, the BIM action steps connected to the project stages are explained. A more complete overview of all the BIM action steps is provided in Appendix A.

4.1.1. Tender stages

In the tendering of projects, potential projects Strukton Civiel is willing to participate in are identified, possibly promoted to a tender and then an offer is developed and given to the client. The project stages adopted during the tender are provided in Figure 4.

[1] This source comes from the intranet of Strukton Civiel and is not publicly available

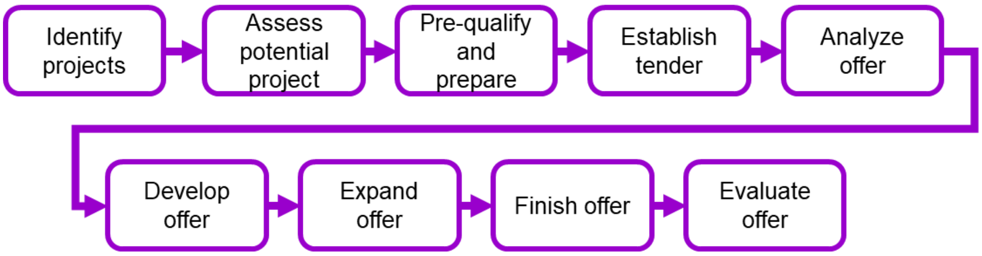


Figure 4: Baseline tender stages of design and construct projects as seen from Strukton Civiel (adoption from document management system Mavim used at Strukton Civiel)

The BIM process is initiated as soon as the *assess potential projects* stage commences. During this stage, the prospect owner and business manager approach potential strategic partners, engineering agencies and subcontractors and intentions in terms of the use of BIM are made clear. In the *pre-qualify and prepare* stage these partnerships are secured by the contract manager or the purchaser and BIM collaboration agreements are established in a BIM action plan. These agreements include the scope of the model, the software programs used, the allocation of modelling and coordination responsibilities, and finally the predetermined LODs that are adopted in the tender. This stage ends with go/no-go decision-making to determine whether the potential project is promoted to a tender.

In case the potential project is promoted to a tender, the *establish tender* stage commences. Depending on the project budget a tender management plan will be developed at this stage and the BIM action plan is further elaborated. The tender management plan describes the strategy, choice of strategic partner, tender organization, planning, budget, risks and financing. The aim of this plan is fourfold (Strukton Civiel, 2020)[1]. Firstly, it is used to identify the client, the demand of the client, the competition and to communicate this information to the involved tender team. Secondly, it is used to define the strategy for winning the tender. Thirdly, it is used to describe the tender approach. Finally, it is used to manage the tender and ensure an offer that is of acceptable quality.

In the *analyse offer* stage it is determined whether the quality of the delivered 3D models is sufficient to apply project structures and quantity take-off. These project structures include the System Breakdown Structure (SBS) and Work Breakdown Structure (WBS). The SBS is a hierarchical decomposition of the to be realized system into different objects. The WBS is a hierarchical decomposition of all the activities required to realize the system. The SBS is connected to the 3D model and the WBS is connected to the 4D model. After this stage, the schedule made by the planner is used as input to develop the 4D model. The latter is done by the BIM representative of the project, so either the BIM coordinator, director, external party or a combination. The final BIM step in the tender stages is the generation of the quality take-off of the building quantities by the cost estimator, purchaser and BIM representative to establish an integrated budget.

[1] This source comes from the intranet of Strukton Civiel and is not publicly available

4.1.1. Realization stages

If Strukton Civiel is awarded the tender, the realization stages are initiated. These stages are shown in Figure 5.

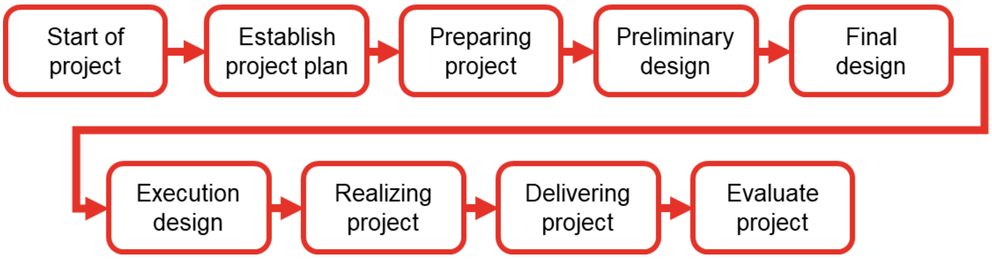


Figure 5: Baseline realization stages of design and construct projects as seen from Strukton Civiel (adoption from document management system Mavim used at Strukton Civiel)

During the *start of the project* stage, the project team is composed and the project plan is developed. Then, in the *establish project plan* stage the BIM execution plan is developed by the BIM representative of the project. Two plans from two different projects (PHS Rijswijk-Delft and the reconstruction of Groningen train station) were studied. The plans studied include at least the following agreements (Strukton Civiel, 2020)[1]:

- The goals of using BIM for the project;
- The BIM uses (both 3D and 4D) that are adopted in the project;
- The division of the BIM roles for the project;
- The software that is used;
- The predetermined LODs adopted per object;
- The project basepoint (X and Y reference point) adopted.

Besides, the SBS and WBS structures are updated at this stage and the connection to the BIM models is established. Moreover, arrangements in terms of site surveying are made. This information obtained could then be used to create a 3D model of the existing situation, which happens in the *preparing project* stage.

The following stages are the *preliminary design* until the *final design* stages. During these stages, the design progresses with intermediate steps. In the *preliminary design* and *final design* stages instruction on how to use BIM360, cloud-based software to visualize the 3D models is given. As the design progresses, so does the 3D model with the corresponding predetermined LODs as established in the BIM execution plans. Once the models are created, 3D clash detection is performed. Then, the phasing sequence is developed and is followed by the constructability analysis. The development and use of a 4D model are not enforced at the *preliminary design* and *final design* stages but is proposed as a useful instrument to support these actions. The same accounts for the validations of the designs and the drafting of the critical plans (such as visualizing temporary works) in 4D. The project baseline suggests its potential added value, but its use is not enforced in the processes.

In the *execution design* stage, the 3D model is developed and, similar to the previous stages, 3D clash detection is performed. At this stage, the development of the 4D model is advised for the execution plans and critical high-risk activities. Moreover, a step is included where the traffic measures are established and supported by the 3D/4D model. Furthermore, a step is included where the 3D/4D model could be useful for communication with stakeholders (client and public).

After these stages, the realization of the project starts on-site. Construction communication with the 4D model is suggested during the *realizing* stage. When construction is finished, the product is handed over to the client. During this *delivery* stage, the 3D/4D model could be transferred to the client as part of the configuration management database when desired. Finally, the BIM360 documents are archived alongside all the other documents used.

To summarize, this section described the processes behind the use of 4D BIM, including the 3D BIM steps. However, the document study lacks more detailed descriptions of 4D uses. This is where the case studies fill in, which are treated in the following section.

4.2. Case studies

This section provides the results from the case studies. Table 3 summarizes the main findings of this section. The information provided in this section is based on the conducted interviews. References to the cases and corresponding interviewees are used as sources using case and interviewee numbers (see Table 1 in Chapter 2 for these numbers). More detail on the individual cases are provided in the interview reports in Appendix B.

4.2.1. Case descriptions

This subsection provides a short description of what the cases are about and what the main focus of BIM was for these cases.

- **Case 1**: This project (tender stages only) concerned the removal of the Roggebotsluice and the replacement of the provincial road N307 and the bridge that crossed the waterway. BIM use was mainly focused on the quantity take-off for soil volumes. It was mentioned that by using the 3D and 4D models, the project team was able to identify a design mistake by the client (interviewee 1). The vertical alignment design of the bridge was incorrect and implied that ship passage under the bridge was impossible. As a result, the bridge had to be constructed at a higher elevation and, therefore, the calculated price was much higher than anticipated. In terms of the 4D uses as found in the literature, this case applied five of the twelve 4D uses, of which one just partly. One remark that can be made when comparing these uses is that the 4D site layout was applied to determine logistical clashes. So 4D site layout could be seen as an intermediate step before 4D clash detection can be applied if the latter is applied to determine logistical clashes.
- **Case 2**: In this D&C project (from tender to delivery stage), Strukton Civiel was appointed as prime contractor for train trajectory between Rijswijk and Delft, as part of a program of high-frequency rail transport. For specific sections of the trajectory, the construction phasing required a temporal restriction on train travel. During these tight periods of the construction phase, a robust schedule was essential to prevent delays (interviewee 3). In addition to the tight schedule, the available working space was limited, causing the project team to find solutions that allowed construction in such a small site layout. For these high-risk activities and sections, a 4D model was developed. This was done for the master schedule and the look-ahead schedule. In terms of 4D uses discovered in the literature, this case applied eight of the twelve 4D uses, of which two just partly. Two remarks can be made when comparing the uses. Firstly, it was mentioned that 4D clash

detection was applied as a result of the development of the slideshow, that was used for team communication (interviewee 3). The spatial-temporal clashes discovered during the process were then used as feedback in improved versions of the planning. Secondly, it was pointed out that the use of a 4D site layout with temporary works and concrete construction joint layout with 4D BIM were all part of the constructability review (interviewee 3).

- **Case 3**: In this D&C project (from tender to delivery stage), Strukton Civiel was responsible for the reconstruction of the train station in Groningen. This case applied seven of the twelve 4D uses, of which one just partly. In terms of complexities, this case is largely comparable to case 2. Parts of the construction phasing required a temporal restriction on train traffic. Similar to case 2, 4D clash detection was the result of the development of the slideshow for team communication (interviewee 4). Besides, it was mentioned that the temporary bridge was part of the 4D site layout to ultimately use it in the constructability analysis (interviewee 5). In terms of cost savings by using the 3D and 4D model, it was mentioned that while direct cost savings were difficult to measure, indirect and more general costs saved can be estimated. As such, the model could reduce the time required to search for the right information if all members have access to the same information. The digital model also reduces the costs related to printing design drawings and usually reduces the duration of meeting compared to using design drawings on paper.
- **Case 4**: In this D&C project (from tender to delivery stage), Strukton Civiel was asked to reconstruct the Rode Vaart canal and the market in the centre of Zevenbergen. The main focus regarding the use of BIM was using the 3D model instead of the 4D model. As such, the utilities and remaining of the old structure underground were modelled in 3D because information on these assets was largely disorganized (Interviewee 6). A 4D animation was not developed for this project. Instead, the 4D aspect was apparent in the addition of the construction phasing to the 3D model. In terms of the 4D uses as discovered in the literature, the case applied four of the twelve 4D uses. Two remarks can be made for this case regarding the 4D uses. Firstly, similar reasons were mentioned to apply both team and stakeholder communication with the 4D model (interviewee 6). Besides, both 4D uses follow the same approach. Secondly, similar to the first remark, the same reasoning was given to apply 4D safety management and 4D constructability management, namely to get more insight into the project (safety) risks. These were identified in team meetings by reviewing activities using the 4D model.

4.2.2. Across-case analysis of the 4D uses

This subsection analyses the 4D uses applied at Strukton Civiel and answer sub research question 1b. The 4D uses as found in the literature are used as reference material.

U1. Stakeholder communication with the 4D model: This 4D use was applied in three of the four cases. In case 3 the 4D model was used as a tool to demonstrate the proposed technical methods and sequence of activities to the client and the neighbourhood (Interviewee 1). This was done to build stakeholder confidence. Case 4 also applied the 4D aspect to communicate with the client and the public. The team showed multiple variations of the 3D model to the client and the public (Interviewee 6). These variants consisted of the 3D model at a different moment in time and displayed the sequence of excavation and construction activities. This 4D use was not applied in case 1 because it was not possible to communicate with the client during the tender procedure due to contractual restrictions.

U2. **Team communication with the 4D model:** This 4D use was applied in all four cases. Case 1 approached this use by discussing the 4D video of the design progression with the team members. In case 1 it was clarified that the visualization was a more effective tool compared to design drawings (Interviewee 1). Case 4 mentioned a similar reason to apply this 4D use and indicated that visualizations are better understandable (Interviewee 6). Case 2 and 3 adopted a similar approach towards this 4D use. In both cases, a slideshow was developed for the overall schedule and for each of the planned engineering-based disruptions, during which train traffic is prohibited. The slideshow contains snapshots of the 3D model, where the coming activities are visualized using colour codes. This slideshow was then used to discuss these coming activities with various realization teams.

U3. **4D clash detection:** This 4D use was applied in three of the four cases and the approaches of the application were mostly similar. In all cases where 4D clash detection was applied, it was used to determine clashes within the construction schedule sequence. Clash detection in case 4 was restricted to clash detection between 3D objects.

U4. **4D site layout:** This 4D use was applied in three of the four cases and its application was different for each case. In case 1 it was applied to determine logistical clashes within the layout. Therefore, its application could be considered as an intermediate step to perform 4D clash detection. In case 2 its application concerned finding solutions regarding the available terrain. This was performed using different versions of the 3D site layout over time. In case 3 this 4D use was applied to visualize where construction takes place over time within the limited terrain available. In case 4 this 4D use was not applied because the project team had insufficient time available (Interviewee 6).

U5. **4D site layout with temporary works:** This 4D use was applied in three of the four cases, although just partly in two of these three cases. Case 1 only applied this 4D use to visualize the installation of a large bridge. This was done in cooperation with a supplier. Similarly, case 3 added a temporary bridge for travellers to the 4D site layout, because this was considered a critical temporary work. Case 2 only modelled temporary sliding tracks which were linked to the overall sequencing. Interviewee 3 added to this that a 4D video would have made this more complete, but was not considered necessary by the supplier because the activity was classified as low risk and because they had sufficient experience in performing the activity without the video.

U6. **4D constructability management:** This 4D use was applied in all four of the cases. In case 1 constructability analysis was conducted to ensure a reliable and safe design (Interviewee 1). In case 3, the constructability was analysed to prevent problematic design issues and, subsequently, provide them with sufficient time to adjust the design if necessary (Interviewee 4).

U7. **4D progress monitoring with point cloud scanning:** This 4D use was applied in none of the cases. In case 2 work-in-progress was compared with the 3D model, but a point cloud was not considered for this project. The other projects either did not consider this 4D use because it occurred in an irrelevant life-cycle stage, or because it was regarded as too much effort.

U8. **4D safety management:** This 4D use was applied in three of the four cases, although just partly in one of these three cases. In case 2 this use was applied to visualize safety zones that had to be guaranteed during activities. Case 3 followed a similar approach but applied this 4D use just partly (Interviewee 5). The difference is that in case 3 safety zones were visualized in the 3D model at a different point in time, and not per activity. Case 4 followed a different approach and applied safety management to identify safety risks during excavation and construction activities.

U9. Concrete joint layout with 4D BIM: This 4D use was applied partly in one of the four cases. In case 2 all the concrete components and construction joints were part of the 3D model (Interviewee 3). By adding the sequencing in which these components are added, the team developed pouring schedules. In comparison to the application as described in the literature, case 2 did not attain an automated process to optimize joint layout and concrete pouring schedules. The other cases either did not apply this 4D use because of a limited budget, an inadequate LOD or a low volume of the required concrete pour.

U10. 4D maintenance tasks: This 4D use was applied in none of the four cases because operation and maintenance were not part of the contracts. In cases 1 and 2 was indicated that the team had to consider future maintenance activities into the design (Interviewee 1 and 3). However, this was not the case for real-time maintenance tasks. It is also worth mentioning that for none of the cases maintenance stages were part of the contract.

U11. Quality control with 4D BIM: This 4D use was applied in none of the four cases. In case 3 was mentioned that the added value of managing quality control in 4D was unknown (Interviewee 4). In case 4 was mentioned that inspection data was not registered

U12. Option evaluation of decommissioning alternatives with 4D BIM: This 4D use was applied in none of the four cases. This 4D use is applicable at the end of a product's life-cycle. However, decommissioning was not part of the contract of any of the analysed cases. Therefore, this 4D use was not considered for any of the cases.

4.2.3. Project characteristics influencing 4D BIM

This section compares the project characteristics obtained from case studies interviews that influenced the use of 4D BIM. Seven project characteristics were recognized from the case studies, which are explained below. One project characteristic was obtained from the expert session. In Table 3 the project characteristic (abbreviated as PC) described above has been linked (whenever possible) to the 4D uses applied in the analysed cases.

PC1. The experience of the project team in working with 4D may influence the use of 4D. This was discovered in the expert session. The effort required to use 4D is dependent on the availability of experienced employees and is a characteristic that should be considered when deciding to use 4D.

PC2. The availability of a 3D model and/or point cloud may influence whether 4D BIM is adopted. In all of the cases, the project team was provided with a 3D model or a point cloud. However, specifically from case 1 can be learned that the availability of the point cloud was the decisive factor to make use of 3D and 4D models. From case 3 was found that the 3D model was not used to its full potential, because there was a mismatch in the project base point used by the client and the contractor.

PC3. Contractual characteristics may influence the decision to use 4D BIM. This can be learned from all cases. In case 1, the project team was able to score Most Economically Advantageous Tender (MEAT) criterion points on their tender document regarding the robustness of the schedule. Therefore, the decision was made to convert the 3D model into a 4D model. Moreover, some of the 4D uses, such as 4D maintenance tasks and option evaluation of decommissioning alternatives with 4D BIM, were not applied in any of the cases due to contractual obligations. This was because these 4D uses are applicable in life-cycle stages that were not part of the contract.

PC4. **Tight site conditions** may influence the decision to use 4D. It was mentioned that the limited terrain available in case 2 caused the project team to apply a 4D site layout (Interviewee 3). As such, they aimed to find solutions to efficiently arrange the positioning of the equipment within the limited site layout.

PC5. **Tight schedules** that have to be followed may influence the use of 4D BIM. This was evident in cases 2 and 3. Both cases involve periods where train traffic is temporarily restricted due to planned engineering-based disruptions activities. During these activities, it is essential to prevent problematic situations and possible delays. For challenging schedules, it was urged to make use of 4D software to mitigate the risk of problems and delays (Interviewee 3).

PC6. **A complex design and sequence** were recognized as a characteristic that could influence the use of 4D BIM. From cases 2, 3 and 4 can be learned that the 4D model helped stakeholders and the project team understand a complex design more easily.

PC7. **Public interests** could influence the use of 4D BIM. This can be learned from cases 2 and 3. In case 2 it was mentioned that the 4D model presumably increased confidence from the client. In case 3 it was mentioned that it was of large importance to guarantee a train passenger flow with a width of 5 meters at the north side of the station (Interviewee 5).

PC8. **Uncertainties underground** in terms of existing underground structure or utility networks offer useful possibilities for 4D BIM. This knowledge is obtained from case 4. In this case, it was mentioned that the main complexity of this project was the uncertainties underground (interviewee 6). The old sheet piles from the previous canal were not removed at that time. This structure may clash with the newly planned sheet pile construction. Besides, the existing utility network had to be replaced in locations where there was a high level of uncertainty about what else is located beneath the ground. To reduce the uncertainty, the project team combined available data in a 3D model and linked the data to the sequencing. Using the 4D model, this information is then shared with the project team, public and client.

4D BIM uses found in the literature	Case 1: Tender N307 Roggebot	Case 2: PHS Rijswijk - Delft	Case 3: Groningen Central Station	Case 4: Roode Vaart and market of Zevenbergen
Stakeholder communication with the 4D model	No, because it was a contractual restriction to communicate with the client during the tender procedure using the 4D model *PC: contractual characteristics*	Yes, because it is a useful tool to strategically share (nuanced) information to the client, subcontractors, suppliers and public *PC: complex design and sequence, public interest*	Yes, because the project team wanted to increase the stakeholder's confidence in the design and, therefore, also in the contractor *PC: complex design and sequence, public interest*	Yes, because visualizations are more understandable compared to drawings or text. This was done with multiple variants of the 3D model that display the sequencing of activities over time *PC: complex design and sequence, uncertain underground*
Team communication with the 4D model	Yes, because it is a more effective communication tool compared to design drawings and because the risk and environment manager wanted to use visualizations to discuss their ideas	Yes, because of the tight schedule of activities that involve the train traffic disturbance. This was done with animations and slideshows *PC: tight schedule*	Yes, because they wanted to visualize and discuss the complex design sequencing and activities. This was done with slideshows *PC: complex design and sequence*	Yes, because visualizations are more understandable compared to drawings or text. This was done with multiple variants of the 3D model that display the sequencing of activities over time *PC: complex design and sequence*
4D clash detection	Yes, because it is useful to determine clashes within the schedule in terms of the construction sequencing of the road layout *PC: complex design and sequence*	Yes, because clashes were discovered in the process of creating the slideshow. These were used as feedback in improved versions of the planning	Yes, because clashes were discovered in the process of creating the slideshow. These were used as feedback in improved versions of the planning	No, because clash detection was limited to clashes between objects
4D site layout	Yes, because the team wanted to get insight in the logistical clashes	Yes, coarse 3D site layouts variants over time because the team wanted to find solutions regarding the available terrain *PC: tight site conditions, tight schedule*	Yes, because the team wanted to visualize the construction site and the locations where construction takes place over time *PC: tight site conditions, tight schedule*	No, because the team had insufficient time for this 4D use. This also had to do with contractual adjustments that changed the sequencing *PC: contractual characteristics*
4D site layout with temporary works	Partly, just one critical activity was converted to 4D in cooperation with a subcontractor. For the rest of the activities, the tender stages were too early to apply this 4D use. If the available space within the layout and the schedule were more critical, the team would have considered this 4D use for other activities as well *PC: tight site conditions*	Partly, temporary sliding tracks were part of the building method and were modelled in 3D. The 4D aspect was incorporated by adding the sequencing because the team wanted to determine the constructability. A video would have been more complete, but the supplier did not see the necessity as they had plenty of experience and the activity was not considered as high risk	Yes, because the team wanted to visualize critical temporary works, such as a temporary bridge. This visualization can be used in the constructability analysis *PC: tight site conditions*	No, because the team had insufficient time for this 4D use. This also had to do with contractual adjustments that changed the sequencing *PC: contractual characteristics*
4D constructability management	Yes, because the team want to ensure that the conceptual design was reliable and safe *PC: complex design and sequence*	Yes, because the team wanted to find clashes in the early stages of the project. Besides, it was a requirement by the client to review the constructability of the product in terms of maintenance activities after delivery	Yes, because the project team wishes to have better insight into their ideas at an early stage in the project. This gives them time to reconsider and change possibly problematic ideas	Yes, because the project team wanted to get more insight into the project risks. This was done in meetings that were attended by team members responsible for different disciplines. During these meetings, the 3D model variants are discussed

		PC: tight site conditions, tight schedule, complex design and sequence	*PC: tight site conditions, tight schedule, complex design and sequence, uncertain underground*	that display a different moment in time *PC: complex design and sequence, uncertain underground*
4D progress monitoring with point cloud scanning	No, because this 4D use occurs in irrelevant life-cycle stages	No, because work-in-progress is monitored and compared with the 3D model	No, because this 4D use was not considered in the BIM plan and would be too much effort	No, because using a point cloud for progress monitoring was not considered for this project. The as-built situation is drawn in 3D
4D safety management	No, because this 4D use would require a higher level of detail that was impossible in the tender stages	Yes, because the design and planning had to consider several safety zones. The 3D model visualized these zones over time and helped to determine measures for activities in dangerous areas *PC: tight site conditions*	Partly, safety zones are indicated in multiple variants of the 3D model, but not advancing per activity *PC: tight site conditions, public interests*	Yes, because the project team wanted to get more insight into the safety risks during the excavation and construction activities *PC: uncertain underground*
Concrete pouring schedule and construction joint layout with 4D BIM	No, because of the limited budget and design team, the decision was made not to apply this 4D use in the tender stages	Partly, because the team wanted to determine the constructability of the concrete components. Besides, they wanted to align the pouring schedules using the 3D model. However, its application did not include any automated process	No, because the team has not achieved this LOD in the model at the time of the interview	No, because the project did not require larger volumes of concrete pours
4D maintenance tasks	No, not in real-time because this 4D use occurs in irrelevant life-cycle stages. The team did, however, determine and mitigate the risks present during the operation and maintenance of the bridge *PC: contractual characteristics*	No, because this 4D use occurs in irrelevant life-cycle stages. The team did, however, determined the workability for maintenance activities for certain components *PC: contractual characteristics*	No, because this 4D use occurs in irrelevant life-cycle stages that were not part of the contract *PC: contractual characteristics*	No, because this 4D use occurs in irrelevant life-cycle stages that were not part of the contract *PC: contractual characteristics*
Quality control with 4D BIM	No, because this 4D use occurs in irrelevant life-cycle stages that were not part of the contract *PC: contractual characteristics*	No, the quality of the as-built situation is continuously being measured, however, doing so with a 4D model was not considered	No, because it was not considered in the BIM plan and because the added value is argued to be unknown	No, because inspection data was not registered in this project
Option evaluation of decommissioning alternatives with 4D BIM	No, because this 4D use occurs in irrelevant life-cycle stages that were not part of the contract *PC: contractual characteristics*	No, because this 4D use occurs in irrelevant life-cycle stages that were not part of the contract *PC: contractual characteristics*	No, because this 4D use occurs in irrelevant life-cycle stages that were not part of the contract *PC: contractual characteristics*	No, because this 4D use occurs in irrelevant life-cycle stages that were not part of the contract *PC: contractual characteristics*

Table 3: Cross-case table of the case studies

4.3. Most relevant 4D uses for Strukton Civiel

Based on the information gathered from literature and case studies, this section aims to determine the most relevant 4D uses for Strukton Civiel. It is important to filter 4D uses because some uses offer fewer benefits compared to others and because the feasibility of the remainder of this study should be ensured. Prioritization is done by plotting 4D uses on an impact versus effort matrix, as can be seen in Figure 6.

4.3.1. Impact versus effort matrix

The vertical axis represents the expected impact of the 4D uses when implemented in a project. The horizontal axis represents the expected effort in terms of time and money required to implement the 4D uses in a project. These two axes form a matrix of four quadrants: quick wins (high impact, low effort), major projects (high impact, high effort), fill in jobs (low impact, low effort) and thankless tasks (low impact, high effort). The 4D uses on or above the diagonal line are, looking at the impact and effort, the uses that should be prioritized and are considered as most relevant for this research.

The 4D uses were ranked according to the expectations of the researcher after conducting the case studies, as can be seen in the upper matrix in Figure 6. These expectations were tested and validated by experts. During the expert session, it was asked whether the experts agreed, partly agreed or disagreed with the positioning of the 4D uses. In case the experts disagreed with the positioning of a 4D use, the individual indicated where they would move the position of the 4D use to instead. The repositioning of all the experts was averaged and inserted into a new matrix. This can be seen in the lower matrix in Figure 6. Appendix C.2 provides a more comprehensive overview of the results, including the results per expert.

4.3.1. Interpretation of the results

From Figure 6 it follows that Stakeholder communication with the 4D model, team communication with the 4D model, 4D clash detection, 4D site layout, 4D constructability management and 4D safety management (U1, U2, U3, U4, U6 and U8) are considered the most relevant 4D uses. These uses should be prioritized over the rest of the 4D uses and are further elaborated in the design treatment. This is because, looking at the impact and effort, both the research and the experts positioned these uses on or above the diagonal line.

Comparison between results from researcher and experts

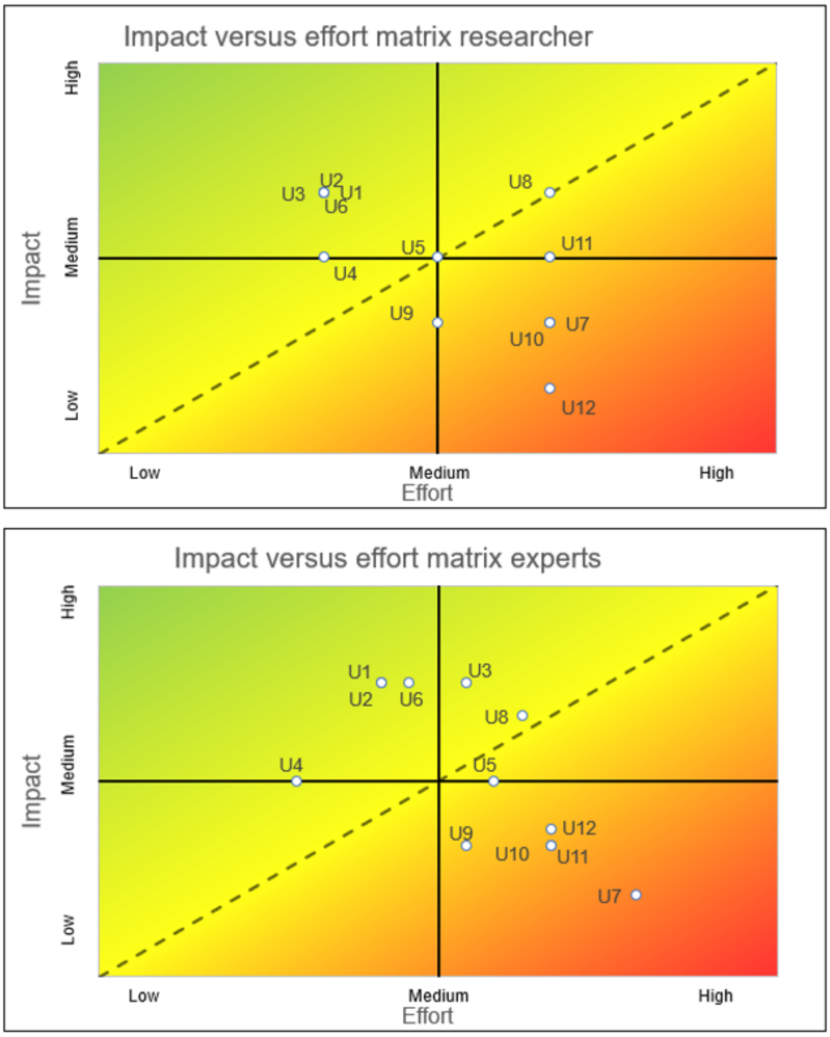
There is an observable difference between the positions of each plot point from the perspective of the researcher and the experts, but it does not influence the prioritization. Merely U5 is disputable, since the expert positioned it below the diagonal line, while the researcher positioned it on top of the diagonal line. On average, the experts considered the 4D uses to require more effort and thought the impact would be higher compared to the predictions of the researcher.

Comparison between results from individual experts

When comparing the results from the BIM managers and project managers, it can be observed that the BIM managers see more potential impact in the 4D uses, but also perceive that the effort required is higher compared to the project managers.

Comments given during the expert session

Some interesting comments on the impact versus effort matrix were given during the session. One of the experts stated that the impact of the 4D uses is highly dependent on the type of project (Project manager 1). This was acknowledged by BIM manager 1, who added: “also the effort required to apply the 4D use is dependent on the experience of the project team. At this moment the required effort is generally high” (BIM manager 1). Project manager 2 also mentioned that experience of the project team influences the required effort but argued differently: “the experience of the employees is growing, so the required effort is lower and the effort will continue to decline in the future” (Project manager 2). BIM manager 1 and BIM manager 2 both mentioned that the effort for some of the 4D uses can be lowered when applied as a cluster. BIM manager 1 mentioned the following: “4D clash detection is never applied as an individual 4D use” (BIM manager 1).



Use #	4D uses
U1	Stakeholder communication with the 4D model
U2	Team communication with the 4D model
U3	4D clash detection
U4	4D site layout
U5	4D site layout with temporary works
U6	4D constructability management
U7	4D progress monitoring with point cloud scanning
U8	4D safety management
U9	Concrete pouring schedule and construction joint layout with 4D BIM
U10	4D maintenance tasks
U11	Quality control with 4D BIM
U12	Option evaluation of decommissioning alternatives with 4D BIM

Figure 6: The impact versus effort matrix

4.4. Sub-conclusion

In this chapter new information was discovered in terms of processes surrounding 4D BIM, reasons to (not) apply 4D uses and project characteristics that can influence the use of 4D, which was not previously discussed in the literature study. Besides, it was determined which 4D uses should be prioritized because they are most relevant for Strukton Civiel at the moment. The analysed information is used to provide an answer to research question 1.

(Research question 1): What 4D uses can be distinguished across the entire life-cycle of infrastructure projects that are most relevant for Strukton Civiel?

Stakeholder communication with the 4D model, team communication with the 4D model, 4D clash detection, 4D site layout, 4D constructability management and 4D safety management are considered the most relevant 4D uses across the entire life-cycle of infrastructure projects of Strukton Civiel. This was the result of the document study, case studies and expert session.

From the document study, it was found that using 4D BIM is embedded in the project life-cycle stages at Strukton Civiel. The company adopts a project baseline that serves as a guideline for every D&C project. The project baseline provides advice on the action steps along the project life-cycle stages that should be followed for successful project delivery. These action steps also include steps that are supported by using 4D BIM. One important step is the development of the BIM execution plan. This plan establishes agreements about (among others) BIM goals, the BIM uses (both 3D and 4D) that are adopted in the project, division of BIM roles, the LOD's per object and the software used. Information about the project baseline is useful to understand when 4D uses could offer support to the processes.

From the four case studies, it was found that the contractor already adopts a large number of the 4D uses discovered in the literature. Besides, reasons to adopt 4D uses were analysed. Based on these reasons, project characteristics have been identified. Furthermore, the analysis yielded the existence of clusters of 4D uses, because some 4D uses are often applied together or because the additional effort required is low. This offers the opportunity to create configurations of 4D uses. The existence of configurations was also acknowledged by the experts during the expert session. The configurations of 4D uses are addressed in the design treatment in the next chapter.

From the expert session, it was found that the following 4D uses should be prioritized: stakeholder communication with the 4D model, team communication with the 4D model, 4D clash detection, 4D site layout, 4D constructability management and 4D safety management. Based on the impact versus effort matrix, these uses are considered most relevant at this moment in time and are considered in the design treatment.

This chapter completes the first step of the Wieringa (2014) cycle. The next step is the design treatment in Chapter 5 that utilizes the gathered information to design the 4D BIM assessment framework.

5. 4D BIM ASSESSMENT FRAMEWORK

This chapter describes the development process of the 4D BIM assessment framework. This development process continuous the methodology from Wieringa (2014). The result of the framework consists of three components: beneficial 4D uses, the feasibility of 4D BIM and configurations of 4D uses. These components are used to develop a practical tool that offers assistance in determining what 4D uses should be further investigated.

First, the design requirements and aspects are defined in section 5.1 to answer research question 2: what are the requirements for the assessment framework? Secondly, the developed assessment framework is described in section 5.2. Thirdly, the practical quick-scan tool that is based on the developed assessment framework is described in section 5.3. Finally, in section 5.4 the information from the aforementioned sections is used to answer research question 3: what is the relationship between 4D BIM, its most relevant 4D uses and different practical situations?

5.1. Design specification

5.1.1. Design requirements

This section provides the design requirements of the proposed solution. This subsection is shared with experts from Strukton Civiel and their feedback is processed accordingly.

Target audience

The framework is mainly intended for project managers that have to make decisions regarding using 4D BIM. Besides managers, the framework could be educational for other employees too. During the interviews, it was mentioned that BIM managers and work planners thought the framework would be useful for them as an overview of the 4D uses and their added value. This would help them to convince project managers that are reluctant to experiment with 4D.

Framework goals

The objective of the framework is to support the decision-making of adopting 4D BIM. During the problem investigation, it was founded that there is a need for a tool to decide what 4D uses are beneficial for various project situations. Based on the data collected, a framework is developed that consists of three components: beneficial 4D uses, the feasibility of 4D BIM and configurations of 4D uses. The framework should result in the following goals for the target audience:

1. Provide insight into the configurations of 4D uses that often applied together;
2. Provide reasons why the 4D uses should or should not be applied;
3. Provide insight into how the 4D uses should be applied;
4. Provide insight into the moment in the project life-cycle in which the 4D uses could be applied;

Framework requirements

The specified requirements are treatment goals (Wieringa, 2014). The specification of the requirements is a design activity by the researcher, which is specified in accordance with the client. Table 4 provides the requirements as specified by the researcher. Bearing the framework goals in mind, arguments are given why the requirements should contribute to these goals.

#	Requirement	Contribution argument
R1	The assessment framework must be useful for project managers	Because some project managers are less knowledgeable about 4D BIM, the framework should be written in an easy-to-understand language and should not be too complex
R2	The assessment framework must describe the configurations of 4D uses that are often applied together	The 4D uses should be combined into configurations to reduce the required effort for implementation
R3	The assessment framework must clarify the feasibility of the 4D configurations	Part of the reasons to apply 4D is assessing whether the project capabilities (3D model or experienced project team) are available to apply the 4D use
R4	The assessment framework must clarify reasons to apply the 4D uses based on the project characteristics	The project characteristics provide reasons to apply or to not apply a 4D use because for some project types 4D is more interesting
R5	The assessment framework must specify benefits (preferably quantified when possible) per project stage that will result from adopting the 4D configuration	The added value of applying a 4D use is also an important reason in assessing whether 4D should be applied or not
R6	The assessment framework must consider 4D BIM for strategic ambitions of the project	Sometimes 4D is applied as a pilot study, as a mean to accomplish business goals or to secure a competitive position in the market
R7	The assessment framework must describe the processes required to use the 4D model	The process map provides insight into the conditions and steps needed to apply the 4D use
R8	The assessment framework must specify the LODs required for the configurations of 4D uses	The LODs are indicators of how far elements of the BIM project should be developed at different project stages, thus providing insight into how the 4D model should be applied
R9	The assessment framework must align the 4D uses to the project stages from the project baseline	To provide insight into the moment in the project life-cycle the 4D use could be applied, it is useful to align these moments to the management system the employees work with. To reduce the complexity of the framework, it framework should distinguish between the realization and tender stage

Table 4: Design requirements

5.1.2. Design structure

Now that the requirements are specified, the solution can be designed. In this subsection, a description is given of the structure of the proposed solution and the aspects that make up the assessment framework. This is done using a desk study, where theory is linked to the results from chapter 4 while bearing the requirements from the client in mind.

Up until this stage, several aspects were founded that make up the assessment:

1. There are various reasons why specific 4D uses are (not) applied in infrastructure projects. This was founded during the literature study in chapter 3 and the case studies

in Chapter 4. These reasons can be translated to conditions to represent different practical situations.

2. Some reasons cannot be related to specific 4D uses but rather indicate the feasibility or potential of 4D BIM in general. This was discovered during the case studies in chapter 4, the expert session in chapter 4 and personal communication conservations. These reasons should be included in this research because they have an important influence on the decision-making of 4D BIM. Similar to the previous aspect, these reasons can be translated to conditions under which 4D BIM should be applied.
3. Some 4D uses are often applied together or have a relationship because the combined effort required to apply the 4D use is decreased. This was founded from the expert session in chapter 4. While there was no data gathered to determine conditions for different practical situations, it is useful to clarify why this combination of 4D uses works well together and how these 4D uses should be approached in the configuration.

Together these aspects form the components of the assessment framework. The client requested to use this framework as input to develop a practical quick-scan tool that offers assistance alongside this research report. The quick-scan tool should give a first idea about the possibilities of 4D BIM for infrastructure projects concerning the three components mentioned above. The client indicated that preference was given to a quick-scan tool of low complexity. During the document study in section 4.1, it was founded that every D&C project consists of many processes that are required for the final project completion. It would be too complex to design a quick-scan tool that describes the entire project life-cycle. This is in line with the study from Wieringa (2014), which recommends studying one factor at a time to understand its capabilities in detail and to ignore the rest. This reduces the complexity of decomposing the design problem. Therefore, the framework only distinguishes between the realization and tender stages (as defined in section 4.1) to reduce the complexity of the framework and the tool. This was aligned with the client, who indicated that because of the uniqueness of infrastructure projects it was difficult to accurately define the process steps when the 4D uses should be applied for every single project.

5.1.3. Sub-conclusion

In chapter 4, case studies and expert sessions were conducted to study the current situation of 4D usage at Strukton Civiel. In this section, requirements were specified to develop an assessment framework that is in line with the needs of Strukton Civiel. These requirements are used to verify the product once it is completed. With this information, research question 2 can be answered.

(Research question 2): What are the requirements for the assessment framework?

The assessment framework should support the decision-making process concerning 4D BIM adoption. The framework is divided into three components: (1) beneficial 4D uses, (2) the feasibility of 4D BIM and (3) 4D uses that could be applied as a configuration. This framework is used as input to develop a practical tool for project managers that is regarded as a quick-scan tool. The quick-scan should provide project managers with an idea in terms of the three components. These 4D uses were considered currently most relevant for Strukton Civiel in subsection 4.4. This tool merely distinguishes between the tender and realization stages to decrease the complexity. The tool should not be too complex to increase its usefulness for project managers that are less knowledgeable about 4D BIM. The research report should provide additional information on the framework when desired. Besides, in chapter 4 it was discovered that some 4D uses are often applied together in configuration to decrease the required effort. The following section provides more information on the developed framework. The subsequent section of this chapter uses this information input to develop a practical tool. This tool translates the conditions into a series of questions that result in an indication of the feasibility of 4D BIM and the ranking of 4D uses that best match the project needs.

5.2. Assessment framework

As mentioned before, this section describes the developed assessment framework and aims to find the answer to research question 3. The framework consists of three components that are part of the assessment for every project: (1) beneficial 4D uses, (2) the feasibility of 4D BIM and (3) 4D uses that could be applied as a configuration.

The following three subsections provide more information on these three components.

5.2.1. 4D uses: conditions under which the uses should be applied

This subsection defines conditions under which the 4D uses should be applied. Conditions are defined based on collected data that provided reasons to (not) apply 4D uses and project characteristics that were matched to the 4D uses. This data originates from literature articles collected in chapter 3 and from case studies analysed in chapter 4. As mentioned before, only the most relevant 4D uses as defined in section 4.3. are included in the design treatment phase. This is because these six 4D uses should be given prioritization over the other 4D uses.

Table 5 provides an overview of all the reasons for choosing to (not) apply 4D uses, project characteristics and conditions under which they should be applied. Subsequently, gathered information from chapter 3 and 4 is translated to conditions under which 4D should (not) be applied. This translation step is further specified in Appendix D. The conditions are written in pseudocode in the right column of Table 5. This text-based design tool is mainly used by programmers, but for this research, pseudocode is useful to transparently show the conceptual design of the framework. The conditional "if then else" structure is used to provide statements that are executed if a certain condition is met. This structure could have been shown as flowcharts but would have been too confusing due to its large structure. Nonetheless, since pseudocode can also be rather confusing, further explanation is given below.

For each 4D use, a minimum of three conditions is given. If a condition is met, the score of the 4D use is increased by 1 and then the next condition is evaluated. If none of the conditions is met, it is advised to dismiss this 4D use. For stakeholder communication with the 4D model (U1), 4D clash detection (U3), 4D safety management (U8) the conditionals are nested within one another. This indicates that if the first condition is not met, usage of the 4D use is immediately disadvised. For example, U1 is not interesting if the contractor is not allowed to use the 4D model as a communicational tool with stakeholders. If this is the case, there is no use in evaluating the other conditions for U1. In one of the case studies, this was not allowed due to contractual restrictions and therefore not applied.

4D use	Data from literature study	Data from case studies			Usage of collected date
	Reasons to apply 4D use	Reasons to apply 4D use	Reasons to not apply 4D use	4D use is relevant for these project characteristics	Apply under these conditions, where the score indicates the attractiveness of the 4D use

Stakeholder communication with the 4D model (U1)	· Help other engineers and non-engineers involved who are likely to be affected by the project (stakeholders) understand the design complexities and the steps required to complete the project (Khwaja & Schmeits, 2014)	· Build stakeholders' confidence in the design using a visualization
		· Share strategic information with stakeholders
			· On some occasions, it not possible to communicate with the stakeholders using the 4D model, because of contractual restrictions	Contractual characteristics (PC3), public interest (PC7), complex design and sequence (PC6)	IF (communication with stakeholders using the 4D model is allowed)
					Score of U1 += 1;
					IF (there are stakeholders that should understand the design complexities and the construction sequence more easily)
					Score of U1 += 1;
					IF (increased stakeholders' confidence in the design of the contractor is desired)
					Score of U1 += 1;
					ELSE (application of U1 disadvised)

Team communication with the 4D model (U2)	· Using a 4D model to support the communication of construction and design details (Hartmann et al., 2007)
	· Discuss the upcoming activities on-site during construction in daily/weekly/monthly team meetings (Umar et al., 2015)
		· Visualize and communicate ideas in multidisciplinary teams where team members work on the same design
		· Discuss tight schedule of activities, involving train traffic disturbance, using animations or slideshows
		· Visualize and discuss ideas of the complex sequencing
			No data	Tight schedule (PC5), complex design and sequence (PC6)	IF (the project design is composed of multiple disciplines)
					Score of U2 += 1;
					IF (the project team should understand the design complexities and the construction sequence more easily)
					Score of U2 += 1;
					IF (the project has to be delivered on a tight schedule of activities)
					Score of U2 += 1;
					ELSE (application of U2 disadvised)

4D clash detection (U3)	· Preventing delays caused by conflicts in the design coordination of multiple parties by combining their different schedules into a 4D model (Hartmann et al., 2007; Trebbe et al., 2015)	· Determine conflicts within the schedule that could significantly affect ongoing activities
		· When clashes are discovered in the process of creating 4D visualizations, they can be used as feedback in improved versions of the schedule
			· When there is no interest in spatial temporal-based clashes and only clashes between objects	Tight site conditions (PC4), complex design and sequence (PC6)	IF (there will be more parties working within a restricted space)
					Score of U3 += 1;
					IF (workflow conflicts are discovered in the process of creating the 4D visualization)
					Score of U3 += 1;
					IF (there are possible workflow conflicts due to separated and different contractor schedules)
					Score of U3 += 1;
					ELSE (application of U3 disadvised)

4D site layout (U4)	· Support the planning of a number of different construction site layouts for different phases, involving changing cranes positions, storage areas, and accesses to the dynamic site (Guerriero et al., 2018)	· Get insight into the logistical issues
		· Find spatial solutions when dealing with tight site conditions
			· When there are contractual adjustments that change the sequencing	Tight site conditions (PC4), tight schedule (PC5)	IF (a number of different site layouts need to be planned for different phases)
					Score of U4 += 1;
					IF (spatial solutions are required for the limited available site layout)
					Score of U4 += 1;
					IF (more insight into logistical issues is needed)
					Score of U4 += 1;
					ELSE (application of U4 disadvised)

4D constructability management (U6)	· Simulating alternative construction sequence to evaluate the overall constructability of the design (Bolshakova et al., 2018)
	· Using the 4D visualization as a project management technique for reviewing construction processes from start to finish during the pre-construction stages (Hartmann et al., 2007)
		· Ensure a more reliable and safe design
		· Get better insight into design and planning ideas at an early stage of the project
		· Get more insight into the project risks
			No data	Complex design and sequence (PC6)	IF (alternative construction sequences should be simulated to evaluate the overall constructability of the design)
					Score of U6 += 1;
					IF (more insight into the project risks is needed)
					Score of U6 += 1;
					IF (more insight into design and planning ideas of the project is needed at an early stage)
					Score of U6 += 1;
					ELSE (application of U6 disadvised)

4D safety management (U8)	· Reduce collision risk of moving or rotating machinery (Hu et al., 2011)
	· Requires a higher LOD where the 4D model describes activities on a daily level (Choe & Leite, 2017)
		· To visualize safety zones over time and support determining measures for activities in dangerous areas
		· Get insight into the safety risks during construction and excavation activities
			· Requires a high LOD, that is often not attainable in the tender stages	Uncertainties underground (PC8), tight site conditions (PC4), public interests (PC7)	IF (the project stage is not the tender stages)
					IF (safety awareness among project participants has to be increased)
					Score of U8 += 1;
					IF (the design has to consider safety zones over time)
					Score of U8 += 1;
					IF (the project is concerned with high safety risks during construction and excavation activities that should be visualized)
					Score of U8 += 1;
					ELSE (application of U8 disadvised)

Table 5: Reasons for choosing (not) to apply 4D uses and conditions under which they should be applied

5.2.2. Feasibility of 4D BIM: conditions under which 4D BIM should be applied

During the research period, reasons for choosing to apply 4D BIM were identified that cannot be related to specific 4D uses, but rather indicate the feasibility of 4D BIM in general. These reasons should be included in this research because they have an important influence on the decision-making of 4D BIM. Therefore they are considered as conditions to apply 4D BIM. The following five reasons were distinguished:

- **The project team is experienced working with 4D** (PC1, section 4.2.3.). The effort to work with and use a 4D model is reduced when the project team has experience working with 4D. Initially, high investment is required to apply 4D, but when the project team becomes more experienced with 4D, the effort reduces and the added value becomes more evident. Therefore the availability of experienced employees is a reason that should be considered.
- **A usable point cloud and/or 3D model is already supplied by the client** (PC2, section 4.2.3). In case the client already supplied the contractor with a point cloud and/or a 3D model of the current situation, the effort to develop a 4D model is reduced. It is important to realize that the transition from a point cloud to a 4D model requires more effort compared to the transition from a 3D model. This is because the 4D model cannot directly be developed from the point cloud and needs to be converted to a 3D model first.
- **The project team is working with a 3D model** (project manager, personal communication, January 13, 2021). Besides the availability of a 3D model, it is important to consider whether the project team will be applying 3D uses as well.
- **The SBS and WBS project structures are applied in the project** (project manager, personal communication, January 13, 2021). When the SBS is linked to the 3D model and the WBS is linked to the schedule, it allows (semi) automated linking of relations between the schedule and the 3D model. While this is not required for every single project, it generally eases the development process of a 4D model.
- **4D is a strategic ambition for the project** (project manager, personal communication, January 8, 2021). For some projects, 4D is an opportunity from a strategic point of view and is something to consider to maintain a competitive position in the market. Sometimes the client awards MEAT points in the tender offer for having a robust schedule. Therefore adopting 4D in a project could be attractive as a means to increase the probability to secure this tender. In different circumstances, it could be advantageous to adopt 4D in a project to gain experience with 4D BIM. This knowledge and experience can later be used as verified evidence to secure future tenders.

It is important to realize that there are some simplifications in the aforementioned reasons to apply 4D BIM. The complexity of the framework can be increased by further specifying different circumstances. As such, the SBS and WBS project structures might not be necessary for the purpose of the 4D model in some situations. Because of the simplifications in the conditions, there are deviations possible where the framework is not a completely accurate representation of reality.

The aforementioned reasons are translated to pseudocode conditionals in Table 6. Instead of providing a score to a specific 4D use, these conditions increase the score of 4D BIM in general terms if a statement is met.

Apply 4D BIM under these conditions

IF (the project team is experienced working with 4D)
        Score of 4D BIM += 1;
IF (a usable point cloud and/or 3D model is already supplied by the client)
        Score of 4D BIM += 1;
IF (the project team is working with a 3D model)
        Score of 4D BIM += 1;
IF (the SBS and WBS project structures are applied in the project
        Score of 4D BIM += 1;
IF (4D is a strategic ambition for the project)
        Score of 4D BIM += 1;
ELSE (use of 4D BIM not advised)

Table 6: Conditions where the score indicates the feasibility of 4D BIM in general terms

Both the conditions from Table 5 and 6 are an important input to develop the assessment framework quick-scan tool, which is explained in a later section of this chapter. Before this quick-scan tool is covered, the following subsection provides an analysis of configurations of 4D uses that are often applied together.

5.2.1. Configurations of 4D uses: combining uses as a configuration

The previous two subsections covered the reasons to (not) apply 4D uses and 4D in general terms. In case the decision was made to use one of these 4D uses, it might be useful to also consider other uses that can easily be applied together. As mentioned before, some 4D uses are often applied together or have a relationship because the additional effort required to apply the 4D use is low.

Using the information gathered from the document study, case studies and the expert session configurations in terms of 4D uses were defined. Several development iterations resulted in the configurations as given in Table 7. The intermediate steps are given in Appendix C.3.

#	4D configuration	Cluster of these 4D uses
1	Design and schedule understanding	Stakeholder communication with the 4D model (U1), team communication with the 4D model (U2)
2	Risk mitigation	Team communication with the 4D model (U2), 4D clash detection (U3), 4D constructability management (U6), 4D safety management (U8)
3	Planning construction sequence	4D site layout (U4), 4D constructability management (U6), 4D safety management (U8)
4	On-site safety management	4D safety management (U8), 4D site layout (U4)

Table 7: Configurations of 4D uses

The remainder of this subsection aims to describe for each configuration why this combination of 4D uses works well together and how these 4D uses should be approached in the configuration.

Configuration 1: design and schedule understanding

This configuration is composed of U1 and U2 and concerns supporting the communication of the project design and planning with stakeholders (such as neighbourhoods, clients and subcontractors) or project teams using the 4D model. When the contractor decides to create a 4D model that is used during meetings with project team members there is little effort required to showcase the design complexities to stakeholders. The same could be mentioned with the order reversed. Therefore, these 4D uses could be applied as a configuration. This configuration was positively validated by four out of the four experts.

This configuration is relevant for both early stages in the project life-cycle when the design is still in development and for later stages when the final design is executed. From the case studies, it was founded that the video of the 4D model was a useful tool to share strategic information. Depending on the contractual restrictions and procedure during the tender stages, this video could support the communication of the bidding aspect during meetings with the client. Besides, a video could be part of the final tender offer to showcase 4D visualization of the developed bid. In the realization stages, the 4D model could be used as part of the design evaluation of the preliminary or final design to get a better grasp of the design over time. Next to the client, the video could also be shown to other stakeholders such as the neighbouring buildings, subcontractors or suppliers.

Configuration 2: risk mitigation

This configuration is composed of U2, U3, U6 and U8 and can be understood as part of risk management, usually done after risk identification and risk analysis. 4D could be integrated into risk mitigation and reduce the risks associated with design errors and issues that occur during construction (Sloot et al., 2019). This configuration was positively evaluated by three out of the four experts, albeit partly by the other expert.

This configuration is composed of the aforementioned 4D uses because all these uses contribute towards a more complete risk mitigation strategy to reduce the potential impact of the risk or increase the control of risk. Firstly, 4D clash detection reduces the conflict risk of multiple parties working at the same time within a limited place. Secondly, the addition of team communication refers to sharing potential conflicts in the design and schedule between team members. In two of the case studies, workflow clashes were discovered during the development of a slideshow of the construction sequence. These conflicts were distributed between team members using marks-ups that were visible to all team members. So there is an interaction between U2 and U3, where the 4D clashes are detected during the application of team communication. Thirdly, by adopting safety management into the risk mitigation strategy, safety zones can be visualized and measures can be determined for dangerous activities. For example, if a dangerous excavation activity is scheduled at the same time as another seemingly low-risk surveying activity, the surveyors are exposed to a potential hazard (Choe & Leite, 2017). Fourthly, 4D constructability management provides additional insight into the project risks. By evaluating the soundness of the design and schedule at an early stage of the project, the risk profile can be further reduced as was discovered in the case studies. Together these 4D uses form a cohesive approach to risk mitigation strategies.

Configuration 3: planning construction sequence

This configuration is composed of U4, U6 and U8 and concerns planning the construction sequence of activities. The configuration was positively validated by two out of the four experts, albeit partly by the other two experts.

The reason for the cluster of these 4D uses is that the common goal is planning the sequence of activities. Firstly, the site layout in 4D allows for the planning of the storage place locations, equipment positioning and accesses to the construction site. In two of the case projects from the case study, the site layout was converted to 4D to ultimately make use of it in the constructability analysis. Secondly, by applying 4D constructability management, the feasibility of the construction sequence can be evaluated and alternative sequences can be simulated to optimize the planning. Thirdly, by adopting safety management into planning the sequencing process, the safety impact of concurrent activities can be determined. Also, safety zones can be visualized and safe passageways can be planned as was discovered in the case studies. When all these 4D uses are applied together, it offers a complete approach to planning the construction sequence.

This configuration can be applied both during the tender stages as well as the realization stages. Initially, a schedule is made during the tender stages. As information availability increases when the project is promoted to the realization stages, the planning needs to be adjusted accordingly. During both stages, 4D offers an approach to planning the construction sequence. This configuration is connected to the risk mitigation configuration. When risks are discovered during the planning of the construction sequence, they should become part of the risk mitigation strategy.

Configuration 4: on-site safety management

This configuration is composed of U8 and U4 and aims to increase on-site safety awareness of all project participants on the job site. This configuration was positively validated by all four experts.

While this combination of 4D uses resembles the planning construction sequence configuration, the purpose of this configuration is different. That is, this configuration is focused on increasing on-site safety awareness of all project participants, compared to planning the concurrent activities. Safety managers can use visualized outcomes such as 4D safety simulation to show on-site workers potential hazards of their day-to-day activities (Choe & Leite, 2017). The reason for combining these uses is because the site layout provides valuable information, among others the surrounding environment, accesses to the construction site, positioning of equipment or locations of underground utilities. If this information is visualized in 4D, potentially hazardous situations can be discussed with on-site workers.

On-site safety management is better suited to the realization stages compared to the tender stages. This is because on-site safety management is best exercised at a higher LOD where the 4D model describes activities on a daily level (Choe & Leite, 2017). This higher LOD is usually not feasible at the tender stages, as was also discovered in the case studies.

In this section, the three components have been clarified that together form the assessment framework. In the next section, this information is used to illustrate how the assessment framework can be used in practice.

5.3. Quick-scan tool

Using the framework as described in the previous section, this section describes how information from the assessment framework is used to develop a practical quick-scan tool. More in-depth information and screenshots of the quick-scan tool are provided in Appendix E.

5.3.1. Purpose of the quick-scan tool

The purpose of the quick-scan is to provide managers with a first impression about the possibilities of 4D BIM for infrastructure projects. This tool should not be considered as a highly detailed tool that calculates implementation costs or provides instruction on how 4D should be implemented. Instead, the quick-scan should provide a first idea of whether or not 4D BIM is interesting and what beneficial 4D uses suit the practical situation. This is done by answering a questionnaire. The result after answering is threefold: (1) a ranking of 4D uses that are beneficial for the project, (2) an indication of the feasibility of 4D BIM that can be understood as the potential of 4D BIM for the project and (3) a ranking of configurations of 4D uses that are often applied together. These correspond with the three components described in the previous sections since the tool is an adaptation of the assessment framework.

5.3.2. Set-up of the questionnaire

The tool is composed of a set of twenty-four questions, that allow the respondents to select one option from the list of answers. The questions used are all based on the "if-then-else" conditionals described in Tables 5 and 6, which were rephrased as questions. The questions distinguish between the first and second components, the beneficial 4D uses and the feasibility of 4D BIM. There are no questions about the third component: the configurations of 4D uses. This is because reasons or conditions under which to apply configurations were not obtained in this research. Alternatively, a solution to incorporate the configurations is described in subsection 5.3.4. The complete questionnaire, including screenshots and the rephrasing process is provided in Appendix E.

For the first component, nineteen questions (Q1 and Q7 until Q24) are asked to the manager to obtain the ranking of 4D uses. This ranking of 4D uses provides insights into the 4D uses that should be further investigated. This insight should be considered as a first impression of the possibilities of 4D, rather than a complete guideline of how each 4D use should be applied. The questions about the 4D uses are all based on the conditionals described in Tables 5. The tool also follows the same logic as the conditionals in Table 5. This implies that some questions are nested within another question. For example, if the user answered that communication with stakeholders by using visualizations is not allowed during the project in Q7 (question 7), there is no use in answering the other questions about stakeholder communication. In this case, the other questions related to stakeholder communication are skipped. This is done in Microsoft Excel by assigning macros to the answer options of the nested question. The macro runs when the user clicks an option button of the nested questions and then hides or unhides specific rows of the Excel worksheet. Again using the example of Q7, follow-up questions Q8 and Q9 are hidden in the worksheet when the user answered that communication with stakeholders by using visualizations is not allowed during the project. More information on the VBA codes and macros is provided in Appendix E.1.

For the first component, five questions (Q2 until Q6) are asked to the project manager to obtain a general indication of the feasibility of 4D BIM. This indication of the feasibility can be understood as the potential of 4D BIM, which is determined based on questions about the teams' experience with 4D BIM and the availability of a 3D model. The questions about the feasibility are all based on the “if-then-else” conditionals described in Tables 6.

For the majority of the questions, there are three answer options available: no, partly and yes. There is one exception since the purpose of Q1 is to distinguish between the project stages: tender stages and realization stages. This distinction is made because of a difference in the availability of information and project needs. From the literature study and case studies, it was founded that 4D safety management requires a 4D model at a high LOD that is most likely not attainable or required in the tender stages (Choe & Leite, 2017). Therefore, if the respondent is using the tool during the tender stage, then the follow-up questions concerning 4D safety management are skipped using macros.

Based on the answers to these questions, a score is assigned to each 4D use, which is described in the next subsection.

5.3.3. Scoring and weighting of the questions

After all the questions are filled in, the scoring of the two components is processed in the results tab of the Excel tool. Similar to the “if-then-else” conditionals in Table 5 and 6, the score of 4D BIM or the 4D use is increased when a condition is met. Depending on the number of answer options, the scoring is adjusted accordingly. The score of the 4D use indicates the attractiveness of the 4D use for the project and the score of the feasibility indicates that 4D BIM is promising.

The score is also dependent on the weight given to the question. In essence, all questions are equally weighted. However, because of the uniqueness of most infrastructure projects, some aspects are more important than others. Therefore, for each question, the possibility is given to assigning a 50% increase in weight. In case additional weight is given to a question, the score of the other questions is compensated accordingly.

There is one exception to the score and weighting rule. Q1 about the project stage is linked to the U8 4D safety management, but the score of this 4D use is not increased when this condition is met. Just because the project is in a certain stage, does not necessarily imply that 4D safety management is attractive for the project. It merely indicates that the possibility to adopt 4D safety management is available.

5.3.4. Ranking system

The scores assigned to the individual answer are aggregated to obtain a final score of the feasibility of 4D BIM and the 4D uses. The result is visualized in a radar diagram to compare the ranking of the 4D uses. In Figure 7 an example result can be seen. The score of the 4D use is expressed in a percental match to the project needs. The feasibility of 4D BIM is indicated using the colour scheme of the polygon. Green indicates high feasibility, yellow medium feasibility and red low feasibility. The three colours are determined based on the aggregated feasibility score, where lower than 33,33% results in a red colour, between 33,33% and 66,66% in a yellow colour and higher than 66,66% in a green colour. A fading colour scale would have been more indicative but was not a standard feature of Excel and was outside the VBA programming skills of the researcher.

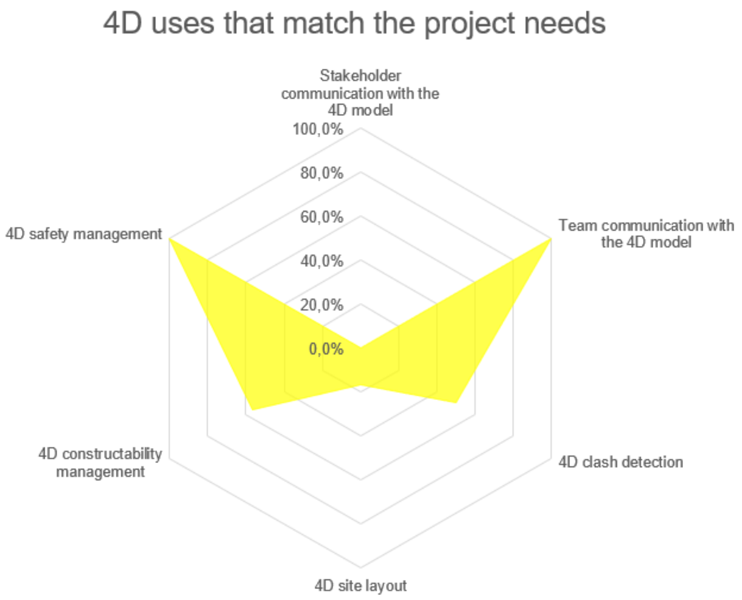


Figure 7: Radar diagram of example results of the quick-scan tool

Figure 7 should be interpreted as follows. The feasibility of 4D BIM scored medium, implying that adoption of 4D BIM in general terms is questionable. If the decision is made to apply 4D BIM, several applications of 4D should be considered. Looking at the scores of the 4D uses, team communication with the 4D model and 4D safety management both scored the highest score possible at 100%. 4D constructability management and 4D clash detection both scored medium with a score between 40% and 60%. 4D site layout and stakeholder communication with the 4D model both scored poorly with a score between 0% and 20%.

Besides the ranking of the two components, the configurations of 4D uses are incorporated into the quick-scan tool as well. The scores of the 4D uses were averaged for each configuration of 4D uses accordingly to indicate what configurations could be considered for the project. The addition of configurations was not visualized in the radar diagram, but the data was included as a supporting table instead.

5.4. Sub-conclusion

This chapter formed the treatment design from the design cycle as proposed by Wieringa (2014). Section 5.1 defined requirements to develop an assessment framework that is in line with the needs of Strukton Civiel. The requirements served as the basis for the framework, which is developed and described in sections 5.2. Subsequently, the assessment framework is used to develop a practical quick-scan tool, which is described in section 5.3. This resulted in the information used to answer research question 3.

(Research question 3): What is the relationship between 4D BIM, its most relevant 4D uses and different practical situations?

The assessment framework described various conditions under which 4D BIM and its uses should be applied based on the information gathered in chapter 4. These conditions form the relationship between 4D BIM, its most relevant 4D uses and different practical situations. Different situations in practice can be imitated depending on the conditions that are relevant for the project. This assessment framework was adapted into a quick-scan tool, which offers a more practical approach to the assessment. The purpose of the tool is to give a first impression of the possibilities of 4D BIM for different kinds of projects. This is done based on a questionnaire composed of twenty-four questions, which answers result in an indication of the feasibility of 4D BIM, a ranking of 4D uses and a ranking of configurations of 4D uses. This tool should not be considered as a highly detailed tool that calculates implementation costs or provides instruction on how 4D should be implemented. Instead, the tool should give managers an idea of the feasibility of 4D BIM and the possibilities in terms of 4D uses that should be further investigated.

With the treatment design phase completed, the final step of this research is to determine to what extend experts consider the quick-scan tool useful in the decision-making process of using 4D BIM. Using the feedback from the experts and using the specified requirements, the quick-scan tool is validated.

6. VALIDATING THE QUICK-SCAN TOOL

The final step of the design circle from Wieringa (2014) is the treatment validation. In this step, the quick-scan tool is verified according to specified requirements and validated with the client. With this information, research question 4 can be answered: what does the verification and validation of the quick-scan tool tell us about the usefulness and added value of the designed tool?

6.1. Verification of the specified requirements

Requirements were specified at the beginning of the previous chapter. With the treatment design completed, these requirements can be verified. This process can be understood as an evaluation of whether or not the designed artefact complies with the specified requirements. This is an activity of the researcher, where an argument is given per requirement. The result is provided in Table 8.

#	Requirement	Verified	Explanation
R1	The assessment framework must be useful for future users	Not yet	Whether the quick-scan tool offers an accessible approach to explore 4D BIM adoption will result from the validation of the framework
R2	The assessment framework must describe the configurations of 4D uses that are often applied together	Yes	The configurations of 4D uses were one of the three components of the framework
R3	The assessment framework must clarify the feasibility of 4D BIM	Yes	Feasibility was considered as one of the three components of the framework
R4	The assessment framework must clarify reasons to apply the 4D uses based on the project characteristics	Yes	Reasons to apply 4D uses were translated to conditions was one of the three components of the framework
R5	The assessment framework must specify benefits (preferably quantified when possible) per project stage that will result from adopting the 4D configuration	Partly	Benefits were present as part of the reasons to adopt certain 4D uses. However, data required to quantify the benefits were lacking
R6	The assessment framework must consider 4D BIM for strategic ambitions of the project	Yes	4D as strategic ambition for the project was considered as a feasibility condition under to apply 4D BIM
R7	The assessment framework must describe the processes required to use the 4D model	Partly	The tool does not provide a precise guideline as to how 4D BIM and uses of 4D should be applied. The configurations do offer insight into how 4D uses could be applied together
R8	The assessment framework must specify the LODs required for the configurations of 4D uses	Partly	LODs were taken into consideration in the configuration component, but because of limited data availability, it was only possible to make a statement about LODs for on-site safety management
R9	The assessment framework must align the 4D uses to the project stages tender and realization	Yes	The project stage distinction was incorporated as a condition for the 4D uses

Table 8: Verification of the requirements

6.2. Validation of the quick-scan tool

The next step was validating the quick-scan tool to determine if the tool meets the needs of the client. The selection of employees consisted of four experts/future users (project leader, planning department manager, BIM director and head of project management) from Strukton Civiel. This group of employees was involved with the research project throughout the research period and are future users of the tool. They were asked to test the tool in a project context for a project in progress or a hypothetical project. Besides, they were asked to answer five closed questions concerning the perceived usefulness and added value of the tool. These questions and answers are provided in Table 9. The answers and additional comments given are discussed in the following subsections. Appendix F provides more details on these answers.

Question	Project leader	Planning department manager	BIM director	Head of project management
Does the quick-scan tool support the decision-making process for 4D BIM adoption?	Yes	Yes	Yes	Yes
Does the tool offer insight into the most relevant 4D uses?	Yes	Cannot answer this question	Partly	Yes
Will you make use of the tool?	Yes	No	Yes	Yes
Will you recommend the tool to others?	Partly	Yes	Partly	Yes
Should the tool be incorporated into the procedures of the company?	No	Yes	Eventually	Yes

Table 9: Verification questions and answer per employee/expert

All of the experts answered that the quick-scan tool supported the decision-making of 4D BIM adoption. The planning department manager added that the tool provided him insight into the potential of 4D BIM and what the possibilities are in terms of (configurations of) 4D uses. The BIM director argued that 4D safety management should not be considered in the calculation of configurations 3 and 4 (planning construction sequence and on-site safety management) if the project is currently in the tender stage. The project leader and the head of project management both commented that the tool mainly gave insight into the added value but emphasized the importance of implementation costs of 4D BIM. These costs are not included in the design and have to be added to the results of the quick-scan.

Two out of the four experts indicated that the tool offers insight into the most relevant 4D uses. The BIM director commented that it is unclear which questions belong together to the same 4D use. The project leader mentioned that the tool lacked a clear understanding of how the scoring and ranking are influenced.

Three out of the four experts answered that they would make use of the tool in future projects. The planning department manager commented that while they did not possess a project role, they would ask project managers about the trade-offs they made concerning the chosen 4D uses for the project.

Two of the experts would recommend the quick-scan tool to others. The planning department manager commented that the tool is useful to engage a discussion about the uses of 4D BIM with the project team. The project leader and BIM director only partly recommend the tool, because of the absence of insight into the implementation costs of 4D BIM. The project leader added that the budget of projects is limited and that adopting 4D BIM implies cutting expenses elsewhere. This assessment is not possible with the quick-scan tool.

Most of the experts answered that the tool should be incorporated into the procedures of the company, albeit in the long run according to the BIM director. The head of project management mentioned that the tool will be incorporated into their process management system to give tender- and project managers advice on whether or not 4D adds value to the project, even supposing that the managers are inexperienced with 4D. This contributes to decreasing the amount of missed opportunities in projects.

6.3. Sub-conclusion

In this chapter, the design cycle from Wieringa (2014) is completed by validating the end result of this research. Section 6.1. verified the quick-scan tool by using the specified requirements from the previous chapter. Section 6.2. validated the quick-scan tool with future users and experts. An attempt is made to answer research question 4 by using the results described in this chapter,

(Research question 4): What does the verification and validation of the quick-scan tool tell us about the usefulness and added value of the designed tool?

Verification of the quick-scan tool resulted that the requirements were mostly satisfied, albeit some partly satisfied. There was no data concerning quantified benefits and LODs specified for the configuration available, which is why some requirements were simplified. The verification of the requirement about the usefulness to future users was part of the validation, which is concluded below.

Validation of the quick-scan tool, the adaptation of the assessment framework, showed that future users/experts were mainly positive about its usefulness and added value. After using the tool in the project context, all of the experts thought that the tool supported the decision-making process of 4D BIM adoption. In addition, it was mentioned that the tool provides insight into the potential of 4D BIM and the possibilities of (configurations of) 4D uses. Besides, another determined added value was to use the tool to engage a discussion about the 4D BIM and its uses. Furthermore, it was also mentioned that the tool will be incorporated into the procedures of the company. However, there were some mixed feelings addressed by the experts. The main piece of criticism was the lack of insight into the implementation cost to balance out the assessment. While the exclusion of the implementation cost was a design decision made because of a lack of data, it could be considered as a future improvement of the tool.

7. DISCUSSION

This chapter provides a discussion on the results of this research. The discussion is focused on four elements: interpretation, implications, limitations and directions for further research.

7.1. Interpretation of the results

The objective of this research was to contribute to 4D BIM adoption by designing an assessment framework that should support the decision-making process for adopting 4D BIM and its most relevant 4D uses in different practical situations. By following the design cycle steps described in the design science methodology from Wierings (2014), this study developed an assessment framework. In addition, information from this framework was adapted into a practical quick-scan tool which was verified and validated. Now that the methodological steps are completed, a reflection can be given on this research.

The designed quick-scan tool is a practical example of how information from the assessment framework could be utilized. This means that other practical adaptations are not excluded. This quick-scan tool was subjected to the practical test through verification and validation but was not subjected to the academic test. The questionnaire was derived from the conditionals from the assessment framework, however, choices made concerning the Excel document are not academically substantiated. This includes decisions made regarding the software program of choice and formulas used to rank the feasibility of 4D BIM and the 4D uses. While this practical quick-scan tool was verified and validated, the framework was not. In terms of the verification, the requirements were specified based on an idea of how the framework would look like. However, after the verification of the framework, it was evident that not all requirements were met. For instance, it was indicated that preference was given to quantified benefits to gain insight into the true value of 4D BIM. However, there was not enough data gathered to measure the benefits of applying 4D uses. In retrospect, it would have been better to distinguish between requirements and wishes to obtain a more realistic result based on the data gathered. Next to the verification, the validation of the tool showed that there is room for improvement because the experts were not unanimously satisfied. However, further refinement of the framework and tool is one of the limitations of this research, which is discussed in section 7.3.

Furthermore, the study aimed to increase awareness of the benefits of 4D BIM. While the assessment framework provides insight into the potential of 4D BIM and the possibilities of (configurations of) 4D uses, it is critical that Strukton Civiel and other practitioners cultivate a learning organization. In the preliminary literature study, it was discovered that time, costs and culture are the main barriers to 4D BM adoption. In this research, it was also discovered that project managers are cautious about investing in 4D BIM due to a limited budget. It is true that investment costs in projects, especially pilot projects, that experiment with 4D BIM for the first time might result in high costs without real insight into the cost savings. However, experience with 4D BIM takes time to grow and pilot projects do not show the true potential of 4D. During the prioritization of the most relevant 4D uses for this research, it was founded that the effort required to set up a 4D model decreased as project teams obtain more experience, thus resulting in lower costs in the long run.

Looking at the cost savings, it was found that both the costs and benefits of 4D BIM are difficult to quantify. However, it is possible to roughly estimate some indirect cost savings based on findings from the case studies. It takes less time to search for the right information by using the 4D model. The ideology of BIM is to have one centrally shared model that is accessible by multiple disciplines, as was found in preliminary research. The project team will work more efficiently and save costs if every project member has access to the same information. Moreover, by using the shared model as a communication tool during meetings, they can be organized more efficiently and reduce the duration of those meetings.

To finish this reflection, is it possible to claim that this research indeed contributed to 4D BIM adoption? The answer to this question is debatable. While the validation of the tool showed that experts generally thought that the tool was useful and planned to make use of the tool, it is difficult to prove that this research truly contributed to 4D BIM adoption. The practical tool is designed to give a first impression of the possibilities of 4D BIM. However, to what extent this results in 4D BIM adoption is difficult to measure.

7.2. Implications of the results

In this subsection is explained how the results fit in with existing theoretical knowledge and how the results could change practice.

Theoretical implications

In preliminary research, it was discovered that the knowledge base around 4D BIM is already substantial and literature covering new possible uses of 4D BIM is ever-growing, but existing literature hardly addresses the relationship between 4D BIM and different practical situations. The results of this research contribute to new insights into this relationship. With the determined conditions, it is possible to reproduce various practical situations. For each of these situations, an idea is given if 4D BIM is interesting in terms of feasibility and possible 4D uses. Besides, configurations of 4D uses are suggested that could easily be applied together. All of these results were not previously covered in the literature.

Practical implications

While the various practical situations reproduced by the conditions under which to apply 4D BIM and 4D uses should provide an approximate representation of reality, some simplifications should be addressed. While these conditions should provide an approximate representation of reality, they could be less relevant in some circumstances. In terms of conditions for the feasibility of 4D BIM, one condition concerned the application of the SBS and WBS. In some circumstances, the SBS and WBS project structures might not be necessary for the purpose of the 4D model. Therefore, there are deviations possible where the framework is not completely true to reality.

7.3. Limitations

There are some limitations to this research that should be addressed. They are described in chronological order of the results from this research.

Firstly, the sub-research question about the 4D uses currently applied at Strukton Civiel was answered using interview data from four case studies. Because of the small sample size of case studies, the answer might not fully represent the entire organization. However, there was not a large number of projects in progress or completion where 4D was applied at the time of analysis. For that reason, the answer to this sub-research question should provide a close approximation.

Secondly, the ambiguity of the 4D BIM could have influenced the results from the case studies. During the case studies, it was discovered that employees had their interpretation of the concept of 4D BIM. As such, one manager noted that using multiple 3D visualizations at a different point in time of the project was not considered 4D because 4D CAD software was not applied. Another manager did consider this as 4D BIM. Therefore, it was discovered that it is important to align the interpretation at the start of the interview.

Thirdly, the most relevant 4D uses are mostly based on the current situation and little attention is given to new 4D uses that are currently not applied at Strukton Civiel. This research determined 4D uses that were considered most relevant for Strukton Civiel at the time of research. While it would have been interesting to provide a prospect of future applications of 4D BIM, this was not addressed in the literature study and the interviews. Although future applications were discussed with employees, there was no concrete data gathered that could have supported these claims. Therefore, it would be limited to speculating what the new possibilities in terms of 4D BIM are.

Fourthly, the assessment framework is designed for infrastructure projects with integrated contracts and does not specifically focus on projects with traditional contracts. These contracts were not included because there was no data available in terms of 4D BIM adoption for this type of project. To the best of the researcher’s knowledge, Strukton Civiel did not apply 4D BIM in projects with a traditional contract. A possible explanation for this can be traced back to the theoretical background of this study. Sloot (2018) reported that for integrated contracts there might be more incentives for the builder to develop a BIM compared to traditional contracts. Because of the restricted data, it is not possible to claim that the results are also directly applicable to projects with traditional contracts.

Finally, from the validation and verification of the tool, it was evident that the tool is merely partly finished as some requirements and some expectations of the client were not fully satisfied. This could imply the initiation of another cycle from the design science methodology from Wieringa (2014) to further refine the framework. Ideally, the cycle is passed through until all requirements are met and the client is fully satisfied. However, this research limits itself to one cycle because of time restrictions.

7.4. Further research

The results of this research could lead to new directions for further research. The following possible directions could be considered:

In the treatment validation, it was found that experts lack sufficient insight into cost savings and the implementation costs associated with adopting 4D BIM. Future research could be conducted in an attempt to quantify costs and benefits. As mentioned previously, while it is difficult to quantify both costs and benefits, it is possible to estimate indirect cost savings due to a decrease in searching time for the right information and an increase in efficiency in meeting durations. Further research could identify more cost savings and try to estimate its impact. In terms of implementation costs, this research could gather the work hours of BIM representatives for the duration of the project to gain insight into the expenditures.

Future research could improve the complexity of the framework to increase its accuracy. This could include studying more project characteristics and reasons to (not) apply 4D BIM to describe more conditions. The literature study of this research mainly focussed on collecting many different 4D uses. However, during the practical part of this research, it was discovered that the relationship between 4D uses and project characteristics that represent different practical situations was more important. Further research could conduct an improved literature study that is focused on this relationship.

8. CONCLUSION

"What does an assessment framework look like that supports the decision-making process for adopting 4D BIM and its most relevant 4D uses in different practical situations?"

This is the main question that this research attempted to answer. Four research questions were used to approach this question. Together this led to the conclusion in section 8.1. In section 8.2 recommendations are given to practitioners such as Strukton Civiel

8.1. Conclusion of the main research question

This research reported a new approach to support the decision-making process for adopting 4D BIM in infrastructure projects by designing an assessment framework and adapting this framework into a quick-scan tool. Both the framework and the tool provide insight into three components: feasibility of 4D BIM, beneficial 4D uses and configurations of 4D uses. The design cycle methodology as developed by Wieringa (2014), provided a comprehensive approach to structure this research in three phases: problem investigation, treatment design and treatment validation.

In the problem investigation phase, uses of 4D BIM were analysed and filtered to determine the most relevant uses for Strukton Civiel at the time of analysis. The literature study (chapter 3) distinguished between twelve 4D uses across the entire life-cycle of infrastructure projects. Since information about these uses in practice was limited in literature, four case studies (chapter 4) were analysed by using these twelve uses as reference material. These case studies provided reasons why 4D uses are (not) applied among a variety of projects. Based on this information, 4D uses were plotted on an impact versus effort matrix which was tested and evaluated during an expert session. Using this matrix the most relevant 4D uses were filtered: stakeholder communication with the 4D model, team communication with the 4D model, 4D clash detection, 4D site layout, 4D constructability management and 4D safety management. Other findings in this phase proposed that there are reasons which cannot be linked to specific uses, but rather indicate if 4D BIM in general terms is feasible. Besides, findings suggested that some 4D uses are seldomly applied individually, but rather as a configuration with other uses to decrease the combined effort.

The treatment design phase used the findings obtained in the previous phase to design the assessment framework (chapter 5). Bearing several specified requirements in mind, the structure of the framework was designed that offers insight into three components: (1) beneficial 4D uses. (2) feasibility of 4D BIM and (3) configurations of 4D uses. Firstly, beneficial 4D uses provide possibilities in terms of applications of 4D BIM. Conditions under which to apply 4D uses were based on reasons to (not) apply 4D uses. Secondly, the feasibility of 4D BIM provides an indication of whether or not 4D BIM is interesting for a project. Conditions under which to apply 4D BIM were determined based on project characteristics. Lastly, configurations of 4D uses that are often applied together because the combined effort required to apply the 4D use is decreased. While there was no data gathered to determine conditions for different practical situations, it is useful to clarify why this combination of 4D uses works well together and how these 4D uses should be approached in the configuration. This assessment framework was adapted into a quick-scan tool, which offers a more practical approach to the assessment. The purpose of the tool is to give a first impression of the possibilities of 4D BIM for infrastructure projects. This tool should not be considered as a highly detailed tool that calculates implementation costs or provides instruction on how 4D should be implemented. Instead, the tool should help in deciding whether or not 4D is interesting and in exploring what the options are in terms of 4D uses that add value to the project. This is done based on a questionnaire composed of twenty-four questions, which answers result in an indication of the feasibility of 4D BIM, a ranking of 4D uses and a ranking of configurations of 4D uses.

The treatment validation phase demonstrated that the quick-scan tool is useful and adds value to the decision-making process of 4D BIM adoption (chapter 6). While experts and future users were generally satisfied with the designed product, they did emphasize the importance of balancing the assessment by estimating the implementation cost of 4D BIM. While the purpose of the quick-scan tool was restricted to a first impression in the decision-making process, it is important to realize that project teams have a limited budget at their disposal. Therefore, estimating the implementation costs is an activity that should be considered after completing the quick-scan. Further research could initiate another cycle from the design science methodology to include these costs. Despite the absence of the implementation costs, the tool provides insight into the potential of 4D BIM and what the possibilities are in terms of (configurations of) 4D uses. It was mentioned by the commissioner of this research that the tool will be incorporated into the process management system of Strukton Civiel to give tender- and project managers advice on whether or not 4D adds value to the project. This way the tool contributes to decreasing the amount of missed opportunities in projects while remaining accessible for managers to explore possible uses of 4D BIM.

In short, the content of this conclusion has been summarized in Figure 8.

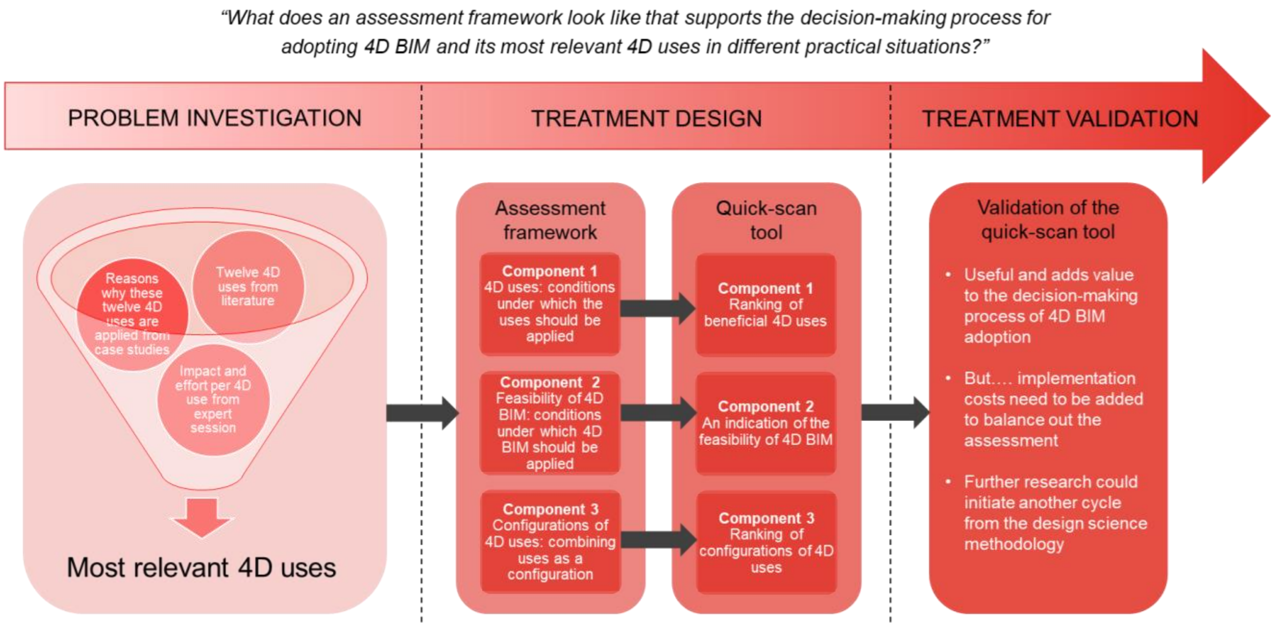


Figure 8: Overview of this research

8.2. Recommendations for practitioners

Based on the results of this research, the following recommendations can be given to Strukton Civiel and other contractors that aim to increase 4D BIM adoption.

The company should incorporate the quick-scan tool into the procedures of Strukton Civiel as the treatment validation showed that employees thought that the quick-scan tool should be incorporated into the procedures of Strukton Civiel. Therefore it is advised to incorporate the quick-scan tool into the project baseline that describes the processes and procedures concerning the BIM action steps. The project baseline was analysed as part of the document study. In this study, it was discovered that a BIM execution plan is established at the start of the tender and realization stages. This plan includes the BIM uses (both 3D and 4D) that are applied in the tender or project. This could be a fitting moment in the project life-cycle to refer to the quick-scan tool.

If the company wants to increase awareness of the benefits of 4D BIM, it is important to cultivate a learning organization that takes the time necessary to adopt 4D BIM. While investment costs in projects, especially pilot projects, that experiment with 4D BIM for the first time might result in high costs without the real insight into the benefits, experience with 4D BIM takes time to grow and pilot projects do not show its true potential. The effort required to set up a 4D model decreased as project teams obtain more experience, thus resulting in lower costs in the long run.

Concerning the learning organization, a 4D BIM workgroup was set up within the company during the research period that scheduled periodical meetings. During these meeting employees that are working on different projects discussed the progress of 4D modelling within their project and shared the issues they encountered. Possible solutions were shared to increase the learning capabilities of the project members. This also increases motivation to employ 4D BIM and keeps the less experienced employees engaged. All in all a step in the right direction, which is recommended to all construction companies that aim to increase BIM adoption.

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APPENDIX A: DOCUMENT STUDY – BIM ACTION STEPS IN PROJECT BASELINE

In Appendix A, an overview is given of the BIM action steps in the project baseline used by Strukton Civiel. The result is provided in Table A1 for the tender stage and in Table A2 for the realization stage.

Tender stage	Step	BIM action present	Role responsible for completion
Assess potential projects	Approaching strategic partners, subcontractors and engineering agencies	Initiate BIM collaboration intentions with the design agencies	Prospect owner and business manager and BIM representative
Pre-qualify and prepare	Capturing strategic partners	Establish BIM collaboration agreements with design agencies in BIM action plan. These agreements include model scope, the software programs used, allocating modelling and coordination responsibilities and LODs used in tender	Contract manager or purchaser and BIM representative
Establish tender	Establishing systems and facilities	Structuring BIM360 cloud environment. Defining initial project structures, object-type library and 3D library based on LODs	Project controller and BIM representative
	Setting up tender management plan	Further elaborating BIM action plan	Project controller and BIM representative
	Executing tender kick-off	Possibility to give instructions on Relatics and BIM360	Project controller and BIM representative
Analyse offer	Conducting document analysis	Determine if the quality of delivered models is sufficient to apply project structures and quantity takeoff	Project team and BIM representative
	Determining project scope and developing SBS and WBS	Incorporating project breakdown in 3D model on behalf of the planning	Systems engineer and BIM representative
	Updating tender management plan	Further elaborating BIM action plan including the LODs	Project controller and BIM representative
Develop offer	Holding brainstorm sessions about methods and Most Economically Advantageous Tender (MEAT)	Determining possible added value of BIM in MEAT	Project team and MEAT coordinator and BIM representative

	Estimating the costs	Generating quantity take-off using 3D model	Cost estimator and purchaser and BIM representative
	Updating project planning and phasing sequence	Developing 4D model	Planner and BIM representative
Expand offer	Updating SBS and WBS	Updating link SBS and WBS in 3D model	Systems engineer and BIM representative
	Establishing integrated planning and phasing sequence	Updating 4D model	Planner and BIM representative
	Establishing integrated budget	Regenerating quantity take-off using 3D model	Cost estimator and purchaser and BIM representative

Table A1: BIM action steps in the tender stage

Realization stage	Step	BIM action present	Role responsible for completion
Establish project plan	Initiating procedures and establishing sub-plans	Establishing BIM execution plan	Project team and BIM representative
	Structuring systems	Structuring BIM360 environment, Revit and or Civil 3D template	Project controller and BIM representative
	Updating project structures, including SBS and WBS	Arranging connection between SBS and 3D model	Project controller and BIM representative
	Establishing planning	BIM360 coding and outlining phasing sequence	Project controller and BIM representative
	Gathering and purchasing surveying services	Arranging 3D scanning of the environment	Technical design manager and purchaser and BIM representative
Preparing project	Establishing verification and validation plans	Updating BIM execution plan to definite version	Systems engineer and BIM representative
	Gathering and purchasing site measurements	Conducting 3D scanning of the environment	Foreman and BIM representative
	Establish and assessing the existing situation	Creating 3D model of the existing situation	Technical design manager and BIM representative
Preliminary design / final design	Kicking-off design stages	Instruction of BIM360 to project teams	Technical design manager and BIM representative

	Drafting preliminary design / final design	Creating 3D model of preliminary design / final design. In addition, clash detection will be performed using the models in this step	Technical design manager and BIM representative
	Working out phasing sequence and constructability	Use of 4D model possible at this step	Technical design manager and BIM representative
	Performing design validation	Use of 3D/4D/VR/AR possible at this step	Technical design manager and BIM representative
	Drafting delivery plan	Possible drafting configuration management database plan	Project controller and BIM representative
	Drafting critical plans	Visualizing temporary works in 3D/4D/VR possible at this step	Environment manager and BIM representative
	Executing conditioning utility network	Added utility network to the 3D model	Foreman and environment manager and BIM representative
Execution design	Drafting execution design	Creating 3D model of execution design. In addition, clash detection will be performed using the models in this step	Technical design manager and BIM representative
	Drafting execution plans	Developing 4D model for execution plans and/or critical high-risk activities	Planner and work planner and BIM representative
	Drafting plan for traffic measures	Visualizing temporary works in 3D/4D/VR possible at this step	Environment manager and traffic manager and BIM representative
	Structuring communication with stakeholders	Use of 3D/4D model possible at this step	Environment manager and BIM representative
	Drafting format delivery documents	Pilot of using 3D BIM in data transferring	Document manager and work planner and BIM representative
Realizing project	Performing communication with stakeholders	Use of 3D/4D model possible at this step	Environment manager and BIM representative
	Drafting and completing delivery documents	Processing as-built situation in 3D model and configuration management database	Document manager and work planner and BIM representative

Table A2: BIM action steps in the realization stage

APPENDIX B: CASE STUDY INTERVIEWS

Appendix B.1: Interview question (in Dutch)

Alle vragen zijn in de verleden tijd geschreven. Indien het project nog gaande is, moeten ze vanzelfsprekend geïnterpreteerd worden in de tegenwoordige tijd.

Achtergrondinformatie project

1. Wat was je rol en verantwoordelijkheid bij het project?
2. Wie was de opdrachtgever van het project?
3. Wat was kort samengevat de vraag van de opdrachtgever (wat werd er gebouwd)?
4. Onder welk soort contract viel het project?
5. Wat was de grote van het project ten aanzien van de prijs?
6. Wat kan je vertellen over de complexiteit van het project?
7. Had het project verder nog bijzondere eigenschappen?

Gebruik 3D/4D

1. Werd tijdens het project gebruikt gemaakt van een 3D model?
    a. Wat waren de redenen om het wel/niet te doen?
        i. Hadden de projecteigenschappen invloed op deze keuze?
    b. Welke onderdelen van het project werden omgezet naar 3D? Ook de tijdelijke elementen zoals hijskranen en bouwketen?
    c. Tot welke detailniveau (level of development) is het model in elkaar gezet?
2. Werd tijdens het project gebruikt gemaakt van een 4D model?
    a. Wat waren de redenen om het wel/niet te doen?
        i. Hadden de projecteigenschappen invloed op deze keuze?
    b. Welke 4D toepassingen werden er gebruikt en kan je hierbij kort vertellen waarvoor dit werd gebruikt? Denk hierbij aan 4D animatie, 4D planning en/of 4D clash detectie?
    c. In welke mate speelde 4D een rol in het project? Had het een leidende rol of speelde het meer op de achtergrond?
    d. Tot welke detailniveau (level of development) is het model in elkaar gezet?

Projectfasering en achterliggende processen

1. Vanaf en binnen welke projectfases was Strukton Civiel betrokken?
2. In welke fases werd gewerkt met het 3D en/of 4D model?
3. Werd het digitale model aangeleverd door de opdrachtgever? Zo ja, moest er veel aan worden aangepast?
4. Kan je vertellen hoe het BIM proces software-technisch verloopt? Welke software wordt er gebruikt en hoe gaat het in zijn werking?
5. Moest het 3D en/of 4D model regelmatig worden aangepast? Zo ja, leverde dit problemen op?
6. Waren er verder nog problemen met betrekken tot 3D/4D waar jullie tegenaan liepen?

Toegevoegde waarde 3D/4D

1. Wat waren de voordelen die 3D/4D met zich meebracht in desbetreffend project ten opzichte van een project zonder 3D/4D?
2. Wat weet je over de faalkosten die bespaard zijn door het gebruik van 3D/4D?

Appendix B.2: Interview reports of the cases

Provided below are the within-case reports made from the selected four case studies. With permission from the interviewees, the interviews were recorded and translated to a cohesive story of the most important findings.

Case 1: report of tender N307 Roggebot

Information about this case was obtained from interviewee 1 and 2. At the end of each paragraph, the specific interviewee is referenced.

Strukton Civiel Noord & Oost participated in the tender N307 Roggebot. The client consisted of a combination of the province of Flevoland and the province of Overijssel. The project concerned the removal of the Roggebotsluice and the replacement of the provincial road N307 and the bridge that crossed the waterway. Because the current route was nearing its capacity, the road and the passage of the bridge needed to be broadened. The work was to be contracted as a Design & construct (D&C) contract and concerned a price of 65 million. The complexity of this project was characterized by the technique, environment, planning and phasing. (Interviewee 1)

Use of 3D/4D model

During the tender, the project team decided that they would make use of a 3D and 4D model. This decision was made because of several reasons. Firstly, the project team was able to score MEAT points in the robustness of the schedule. Secondly, they wanted to sustain a competitive advantage over their competitors. A 3D and 4D model should contribute to this goal. Besides, the gained valuable experience of using a 3D and 4D model should decrease the investment costs in future projects. Thirdly, the project team was provided with a point cloud file of the current situation by the client. This reduced the investment cost of modelling the project in 3D and 4D. (Interviewee 1)

The 3D model consisted of everything that could be translated to quantities relevant to the tender. In particular, the soil volumes that had to be moved played an important role in the 3D and 4D model. The point cloud served as the baseline, on top of which the new situation was modelled. (Interviewee 1)

The model was developed with a low LOD (LOD 100). This decision had to do with the dynamic nature of tenders. In the beginning, the LOD was coarse and elements that required more detail were adjusted as necessary as the tender progressed. Especially components of the bridge were developed at a very low LOD. (Interviewee 2)

There were three 4D uses applied in this project. Firstly, the phasing was captured in 4D to control the project risks. One of these risks was managing the passage of commercial shipping. The proposed schedule needed to ensure no hindrance to these ships during the construction of the bridge deck. Therefore, the visualization of the 4D model was used to control this risk. Secondly, a video of the progressing design was used as a means for communication with the project teams. This proved to be much more effective compared to the design drawings that were generally used in projects. Thirdly, 4D clash detection was performed to determine clashes in the temporary road layout. (Interviewee 1)

Underlying processes

The project was not awarded to Strukton Civiel Noord & Oost and, therefore, the project team was only involved in the tender phase. They converted the design to a 3D and as soon as they received the point cloud file from the client. The time required to set up the model greatly reduced as a result of having the point cloud. (Interviewee 1)

The BIM modelling process of the infrastructure components was done in Civil 3D software. This was linked to 4D using Navisworks software. (Interviewee 2)

This BIM process was outsourced to an external partner because there was insufficient staff capacity within the organization. A disadvantage of outsourcing the task is that the experience gained from using 3D and 4D is partly lost after the project is completed because the service provider moves on. (Interviewee 1)

Added value of using 3D and 4D

One of the advantages of the 3D and 4D model in this project was the increase in accuracy of the price calculation. Using the model, the project team discovered that the vertical alignment design of the bridge that was provided by the client was incorrect. If they would have used the numbers that were provided by the client, ship passage under the bridge would not have been possible. As a result, the bridge needed to be constructed at a higher elevation and, therefore, the calculated price was much higher than anticipated. (Interviewee 2)

Another advantage of the model was that all the designs were centrally organized in one model. Moreover, the ability to walk through the model and the ability to visually demonstrate the design to all the participants were considered useful benefits. (Interviewee 1)

Case 2: report of project realisation PHS Rijswijk – Delft

Information about this case was obtained from interviewee 3.

The Programma Hoogfrequent Spoorvervoer (PHS), or in English programme high-frequency rail transport, is a large scale project to increase the frequency of train transport across the busiest trajectories within the Netherland. Commissioned by Prorail, Strukton Civiel Projecten was awarded the trajectory between Rijswijk and Delft as the prime contractor, which is one of these busy trajectories. The number of tracks is increased for this trajectory from 2 to 4 tracks. The work is currently in construction and was contracted under a D&C contract.

The project is characterized by multiple complexities. The planned engineering work for this project included changing the track layout. During this period, train transport will be prohibited because the line will be unavailable and unsafe for train transport. For the entire duration of this project, these planned engineering-based disruptions (Trein Vrije Periode in Dutch) will occur multiple times. During these activities, it is essential to have a robust schedule to prevent delays. Also, there was only limited space available in terms of the site layout. The project team had to come up with a solution that allowed construction in such a small area, especially during planned engineering-based disruptions.

Use of 3D/4D model

The main reasons for using a 3D model in this project were to integrate the models of each discipline into a central model and to walk through the model. The latter had several functions.

The model was shared with the client to align the zoning plan that the architect had in mind. Also, a walkthrough session was held with the fire brigades to ensure a safety plan in case of emergencies. Besides, a walkthrough session was held with the design and realization teams.

The 4D aspect was used for several applications.

Firstly, a video was made for the planned activities near Delft Campus that shows the general schedule for this area. This video was used as a tool to communicate with the stakeholders (client, suppliers, neighbourhood) and the design and realization teams. The interviewee mentioned being cautious with the information that is shared with the neighbourhood. The information could lead them to believe that there would be too much disturbance due to construction. Therefore, the information provided in the 4D animation should be nuanced and shared strategically.

Secondly, for each of the planned engineering-based disruptions, a video and slideshow with snapshots were made that showed the sequence of activities in detail. 4D clashes that were discovered in the process were used as feedback in improved versions of the planning. The slideshow with the sequence of activities is presented to the client and the diverse realization teams during the kick-off of each planned engineering-based disruptions. For the first planned engineering-based disruptions that lasted 3 days, 72 snapshots were created that for each hour described the sequence of activities and the position of the equipment.

Thirdly, 4D was used to review the constructability of construction processes. This included determining temporary measures for specific activities. During the hoisting of the roof structures measures were needed, before the joints between the columns and roof sections could be assembled

Finally, applying 4D was an ambition of the organization. They aim to use it in future projects and needed experience in doing so. The project team started following a learning course in Synchro 4D after Strukton Civiel Projecten was awarded the tender.

Underlying processes

Strukton Civiel Project is involved from the tender stage until the delivery stage. The client provided Strukton Civiel Projecten with three 3D models that were part of the whole project. BIM 360 serves as a cloud-based document management system that was accessible by all users. The models were the area where the train crosses Delft Campus, Station Delft, and the industrial zone. Within these models, certain components were further developed until a LOD of 200. Synchro 4D was used in a later stage to create the videos and snapshots in 4D. These snapshots could have been developed using the Revit model. However, it is time-consuming to create 72 different models for the first planned engineering-based disruptions. Therefore, Synchro 4D is a more convenient choice.

The integrated 3D model was an effort from both an external party and from the in-house BIM modeller. A share of the objects (the tracks, bridge and overhead lines) was developed externally and the other share of the objects (site layout with temporary works such as storage place, equipment and physical barriers) by the BIM modeller. The 4D model in Synchro was developed by the BIM modeller, which worked together with the planning and realization teams to determine the sequence of activities and the site layout. The interviewee gave two examples. One of the activities includes installing the electricity and water utility network under the train platform. These have to be installed before the platform copings are placed. Another activity involves moving the storage place to make room for the next. Visualizing these changes over time is a very useful addition to the 3D model.

Added value of using 3D and 4D

The main benefits of using 3D in this project were the ability to integrate the models of the different disciplines into a central model and the ability to have the walkthrough sessions. The 3D and 4D models both revealed several clashed in the design and execution. Without the 3D and 4D model these clashes might not be identified and would have resulted in failure costs. Another benefit of both the 3D and 4D models was the control and gain in trust toward the client, suppliers, and the design and execution teams.

Case 3: report of project train station Groningen

Information about this case was obtained from interviewee 4 and 5.

Strukton Civiel Projecten was responsible as the main contractor for the construction of a new train station in Groningen. The project consisted of a tunnel for bicycles, an underground parking garage for bicycles, a bus underpass and an underground travellers plaza. The work was contracted for the client Prorail under a D&C contract and concerned a price of 110 million. Within the project duration of 3 years, there are 3 large activities with planned engineering-based disruptions where train transport is prohibited. (Interviewee 5)

The project is characterized by multiple complexities. One of these complexities was the system that was partly above and partly below ground level. Concerning the excavation activities, it was uncertain what will be discovered underground. For instance, several archaeological discoveries were found. Another complexity was that the train station building of Groningen was a monumental building. (Interviewee 4)

The passage tunnel under the train station is therefore a high-risk part of the project that had to be considered thoroughly in the design and development stage. Another complexity was the passenger flow with a width of 5 meters at the north side of the station that had to be guaranteed at all times. (Interviewee 5)

Use of 3D/4D model

The use of a 3D model was a requirement from the client. Also, its use provides opportunities to integrate and improve the designs from multiple disciplines. These disciplines consist of the architectural, structural (underground and above ground), MEP (mechanical, electrical and plumbing) and civil (surrounding roads, plaza and bus and train platforms) designs. Besides, the use of a 3D model decreases the duration of the design stage and increased the chance that conflicts within the design are discovered (for instance a clash between concrete components and installations). (Interviewee 4)

4D has not been applied yet but will be adopted in this project having several functions. Firstly, it will be used to determine the constructability or the feasibility of the planning and design. By applying 4D in this project, the project team expects to have better insights and reconsider and change certain ideas at an early stage in the project that could cause problems later on in the project. Secondly, it will be used as a communication tool to convince the client and other stakeholders of the proposed methods and sequence of activities, because they wanted to increase their confidence in the design and, therefore, also in the contractor. Without the 4D aspect, the stakeholders would have to understand the complex planning sheets and design drawings. Thirdly, 4D clash detection was performed to determine clashes present in the overall schedule. (Interviewee 4)

Fourthly, it will be used as a communication tool within the project team. A slideshow will be used to show the sequence of activities with a high LOD for each of the planned engineering-based disruptions. The slideshow shows a snapshot of the 3D model in addition to the activities that will take place on a weekly basis. (Interviewee 5)

Underlying processes

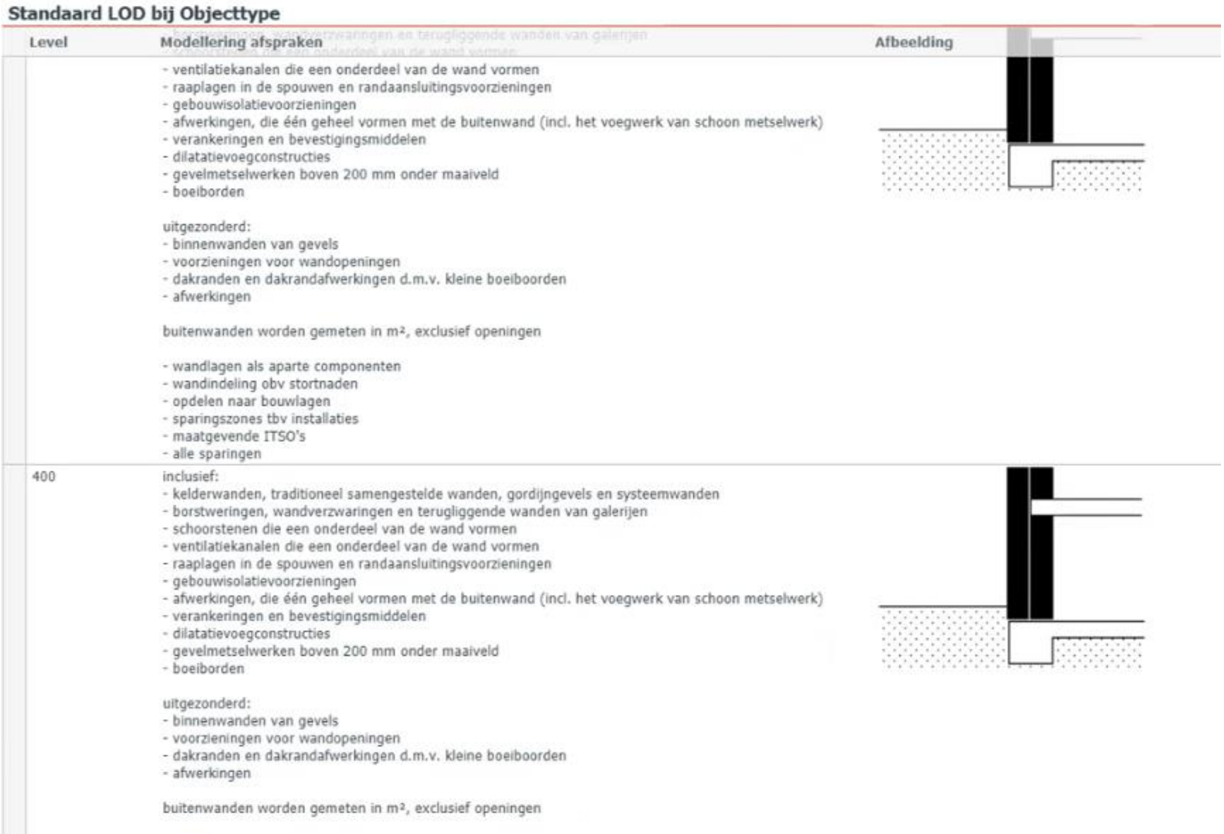
Strukton Civiel Project is involved from the tender stage until the delivery stage. The 3D model was developed in the tender stage but was not used at its full potential until after the tender stage. The project team was provided with a 3D model by the client. However, there was a mismatch in the project base point used by the client and the contractor. The project base point is a fundamental part of the project that provides the reference point for all layers of the 3D model. Because of this mismatch, the model provided by the client could not be used at its full potential. The 4D model was developed in the execution design stage, although they wished to develop the model at an earlier stage. (Interviewee 5)

Regarding the software, a multitude of software programs is used to create and manage the 4D model. As for the 3D aspect, Revit is used for all the modelling of the buildings. Civil 3D is used for the civil components, so the surrounding roads, plaza and bus and train platforms. Solibri is used for clash detection and for determining the quality of the model. BIM360 is used to save and share the model documents. Another function of BIM360 is attaching mark-ups or comments to objects that express concerns related to the design. Power BI is used to create an overview of the data extracted from each model. This includes the number of issues and comments within the 3D model and whether or not they have been resolved yet. The BIM coordinator manages these issues and makes sure they are resolved in time. The project planning is worked out in Primavera and is combined with the 3D model in Synchro 4D to ultimately create the 4D model. (Interviewee 4)

The 3D model is created from the system breakdown structure (SBS) and the planning from the work breakdown structure (WBS). The LOD in the 3D model was predetermined for each of the objects present in the model, as can be seen in Figure B1, and progresses alongside the project life-cycle. In the final design, it was determined that some objects receive a LOD of 300 and others a LOD of 350. For some objects, this will be further increased to LOD 400 in the execution design. Similar to the LOD in the SBS, the WBS is worked out until a certain LOD. (Interviewee 4)

However, there was a mismatch between the LOD of the SBS and the LOD of the WBS. This caused issues during linking the 3D model with the planning. In the tender stages, the LOD of the planning should be at a monthly level. In the final design stages, this LOD should be at a weekly level. In the execution design, this LOD should be at a daily level. For efficiency reasons, it is important to set fixed moments during the progression of the design stages, after which the 3D model cannot be adjusted anymore. There were occasions in this project where adjustments were made in the final design, while some members of the project team were already working on the execution design. This resulted in an increased workload. (Interviewee 5)

In addition, this process is currently done manually, which is a time-consuming process. It would be more efficient to apply predefined and custom-made rules to instantly attach tasks to objects in the model. This automatic linking is an endeavour for Strukton Civiel Projecten in future projects. (Interviewee 4)


Standaard LOD bij Objecttype

Level	Modellering afspraken	Afbeelding
	- ventilatiekanalen die een onderdeel van de wand vormen - raaplagen in de spouwen en randaansluitingsvoorzieningen - gebouwisolatievoorzieningen - afwerkingen, die één geheel vormen met de buitenwand (incl. het voegwerk van schoon metselwerk) - verankeringen en bevestigingsmiddelen - dilatatievoegconstructies - gevelmetselwerken boven 200 mm onder maaiveld - boeiborden uitgezonderd: - binnenwanden van gevels - voorzieningen voor wandopeningen - dakranden en dakrandafwerkingen d.m.v. kleine boeiboorden - afwerkingen buitenwanden worden gemeten in m², exclusief openingen - wandlagen als aparte componenten - wandindeling obv stortnaden - opdelen naar bouwlagen - sparingszones tbv installaties - maatgevende ITSO's - alle sparingen	
400	inclusief: - kelderwanden, traditioneel samengestelde wanden, gordijngevels en systeemwanden - borstweringen, wandverzwaringen en terugliggende wanden van galerijen - schoorstenen die een onderdeel van de wand vormen - ventilatiekanalen die een onderdeel van de wand vormen - raaplagen in de spouwen en randaansluitingsvoorzieningen - gebouwisolatievoorzieningen - afwerkingen, die één geheel vormen met de buitenwand (incl. het voegwerk van schoon metselwerk) - verankeringen en bevestigingsmiddelen - dilatatievoegconstructies - gevelmetselwerken boven 200 mm onder maaiveld - boeiborden uitgezonderd: - binnenwanden van gevels - voorzieningen voor wandopeningen - dakranden en dakrandafwerkingen d.m.v. kleine boeiboorden - afwerkingen buitenwanden worden gemeten in m², exclusief openingen	

Figure B1: LOD specified per object (in Dutch)

Added value of using 3D and 4D

The clashes that were detected using the 3D model caused the project team to discover problems early in the project. Besides, mutations to the design are easily implemented using the 3D model. In addition to the clashes and implementing mutations, the 3D model is helpful to communicate potential issues or concerns within the design compared to a difficult to understand 2D drawing. This can be done within BIM360 where comments can be attached to objects that are accessible by all users. (Interviewee 4)

For this project, direct failure costs saved by applying the 3D/4D model were difficult to express. However, indirect and more general costs saved can be estimated in several ways. Firstly, the time spent searching for the right information can be reduced using the BIM model. Secondly, other costs mentioned are the savings in printing design drawing on paper. Thirdly, using the 3D model in meetings are usually shorter in duration and are more clear compared to design drawings on paper or in 2D. (Interviewee 4)

Case 4: report of the reopening of the Roode Vaart and reconstructing the market in the Zevenbergen centre

Information about this case was obtained from interviewee 6.

Strukton Civiel Zuid is responsible for the reopening of the Rode Vaart canal and the reconstruction of the market in the centre of Zevenbergen. The client of this project is the municipality of Moerdijk. The client wants to reopen the port that was present in Zevenbergen but closed forty years ago. This requires excavation work Sheet pile construction. The gap between the existing canal and the new canal will be bridged using a large concrete culvert that allows water to flow underneath the road

In addition to the canal, the client wants to rebuild the market plaza by covering the surface of the plaza with new bricks and reorganizing the underground utility network. The work was contracted under a D&C contract and concerns a price of about 30 million. The complexity of this project was mainly the uncertainties underground. The old sheet piles from the previous canal were not removed at that time. This structure may clash with the newly planned sheet pile construction. In addition, the existing utility network had been to replaced in locations where there is a high level of uncertainty about what else is located beneath the ground.

Use of 3D/4D model

The decision to use a 3D model was made in the tender phase. It was a requirement from the client that a 3D model was part of the Most Economically Advantageous Tender (MEAT) strategy. Another reason to make use of the 3D model was because of the uncertainties in the location of utilities beneath the ground. By combining available data from existing underground infrastructure maps in a 3D model, they aimed to have more insight into what to expect beneath the ground. The 3D model consisted of the sheet pile construction, the relevant road network and the utility network. Clash detection was performed to find clashes between the (new) utility network and the sheet pile construction.

4D was not explicitly applied in this project, however, there were a few variants made of the 3D model to represented the sequence of activities on a broad scale. A 4D video with the 3D model progressing over time was not created for this project. A time-distance diagram was used as an alternative to visualize the planning.

Underlying processes

As previously mentioned the 3D model was developed in the tender stage. Revit software was the chosen software to create the 3D model. Within the 3D model, multiple variants were made that display the sequencing of activities over time.

Added value of using 3D and 4D

The main benefit of using 3D in this project was mainly the improved communication between the project teams and between the contractor, the client and the public. Reducing the risks of discovering unexpected objects during excavation is worthwhile the effort of creating a 3D model. The costs related to possible excavation damage due to unknown objects underground

Benefits related to the 4D model have not been discovered as it has not been applied yet.

APPENDIX C: EXPERT SESSION

Appendix C.1: protocol of the session (in Dutch)

Organisator/onderzoeker: Jesse Peeters
Deelnemers/experts sessie 1: Ron Pieterse, René Krol, Renzo van Rijswijk
Datum van sessie 1: dinsdag 24 november 2020 11:00 – 12:30
Deelnemer/expert sessie 2: Hans van Loghem
Datum van sessie 2: vrijdag 27 november 2020 12:30 – 14:00

Doel van de sessie

Het voornaamste doel van de sessie is om configuraties van 4D toepassingen te bepalen. De configuraties bestaan uit clusters van 4D toepassingen die elkaar aanvullen omdat ze vaak samen worden toegepast of omdat er weinig extra moeite nodig is als de ander al wordt toegepast. Deze zijn door de onderzoeker opgesteld, maar dienen gevalideerd te worden. Hetzelfde geldt voor de invulling van de impact versus effort matrix, die ingevuld is door de onderzoeker en gevalideerd dient te worden door de experts.

Deelnemers

Naast dat de deelnemers al zijn geïnterviewd en bekend zijn met het onderzoek, is het belangrijk om een mix van experts van projectmanagers (Hans van Loghem en Ron Pieterse) en BIM-managers (René Krol en Renzo van Rijswijk) te waarborgen. Hierbij wordt dus gesproken over een heterogene groep. Doordat de deelnemers verschillende achtergronden hebben zullen meningen vaker uiteenlopen en kunnen ze het onderwerp ook vanaf een ander perspectief ervaren. Wegens een afzegging van een van de deelnemers werd er een tweede, individuele, sessie gepland met de desbetreffende deelnemer.

Aanpak

De sessie volgt een gesegmenteerde en dynamische aanpak. Hierbij wordt er telkens een onderdeel gepresenteerd door de onderzoeker, wordt er geëindigd met per puntje de vraag of ze het hier eens/niet eens/deels eens nee zijn. Vervolgens wordt per puntje gevraagd om verdere toelichting bij het vorige antwoord. Hierbij wordt aangehouden dat de onderzoeker in ongeveer 5 min een bevindingen bespreekt, waarna er ongeveer 30 min wordt genomen om de experts aan het woord te laten. Door deze aanpak wordt er geprobeerd om een goede verdeling te creëren van presenteren door de onderzoeker en interactie met de experts. Tevens wordt er zoveel mogelijk geprobeerd iedereen aan het woord te krijgen per onderdeel.

Draaiboek

Het draaiboek dat gevolgd zal worden tijdens de sessie is weergegeven op de volgende pagina in Tabel C1.

Tijd	Onderdeel	Doel	Toelichting
11:00-11:05	Introductie sessie	Uitleg waarom deze sessie plaatsvindt	- Verwelkomen deelnemers - Uitleg doel en format van de sessie
11:05-11:15	Onderdeel 1: presentatie over configuraties	Gevonden 4D toepassingen opfrissen bij de deelnemers en configuraties presenteren	- Iedereen aanwezig is al een keer geïnterviewd en bekend met de besproken 4D toepassingen, maar in het kader van opfrissen worden allen opnieuw kort uitgelegd - Uitleg idee achter de configuraties: clusteren van 4D toepassingen om onderzoek te trechteren - Samenstelling configuraties door onderzoeker presenteren
11:15-11:45	Onderdeel 1: validatie deelnemers	Configuraties valideren	- Per configuratie aangegeven: eens/ niet eens/ deels eens - Per configuratie vragen naar toelichting vorige antwoord
11:45-11:55	Onderdeel 2: presentatie over impact vs effort matrix	Ingevulde impact versus effort matrix presenteren	- Uitleg werking impact vs effort matrix - Mijn ingevulde matrix presenteren
11:55-12:25	Onderdeel 2: validatie deelnemers	Impact/effort matrix valideren	- Per punt op de matrix aangegeven: eens/ niet eens/ deels eens - Per punt op de matrix vragen naar toelichting vorige antwoord
12:25-12:30	Afsluiting sessie		Slot en eventuele uitloop

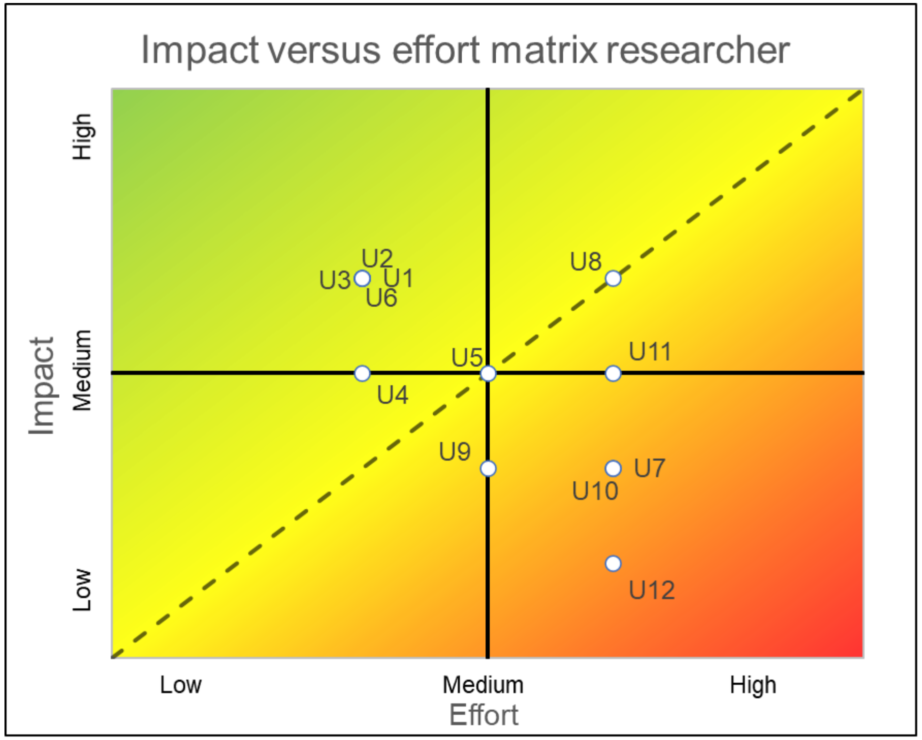
Tabel C1: Draaiboek expert sessie

Appendix C.2: Impact versus effort matrix

Use #	4D uses	Researcher		Project manager 1			BIM manager 1			BIM manager 2			Project manager 2			Experts average	
		Impact	Effort	Agree	Impact	Effort	Agree	Impact	Effort	Agree	Impact	Effort	Agree	Impact	Effort	Impact	Effort
U1	Stakeholder communication with the 4D model	4	2	Yes	4	2	No	5	3	No	5	3	Yes	4	2	4,5	2,5
U2	Team communication with the 4D model	4	2	Yes	4	2	No	5	3	No	5	3	Yes	4	2	4,5	2,5
U3	4D clash detection	4	2	Yes	4	2	No	5	3	No	5	3	No	4	5	4,5	3,25
U4	4D site layout	3	2	Yes	3	2	Yes	3	2	Yes	3	2	No	3	1	3	1,75
U5	4D site layout with temporary works	3	3	Yes	3	3	No	3	4	No	3	4	Yes	3	3	3	3,5
U6	4D constructability management	4	2	Yes	4	2	No	5	3	No	5	3	No	4	3	4,5	2,75
U7	4D progress monitoring with point cloud scanning	2	4	Yes	2	4	No	1	5	No	1	5	No	1	5	1,25	4,75
U8	4D safety management	4	4	Yes	4	4	No	4	3	No	4	5	No	4	3	4	3,75
U9	Concrete pouring schedule and construction joint layout with 4D BIM	2	3	Yes	2	3	Yes	2	3	Yes	2	3	No	2	4	2	3,25
U10	4D maintenance tasks	2	4	Yes	2	4	Yes	2	4	Yes	2	4	Partly*	2	4	2	4
U11	Quality control with 4D BIM	3	4	Yes	3	4	No	2	4	No	2	4	No	1	4	2	4
U12	Option evaluation of decommissioning alternatives with 4D BIM	1	4	Yes	1	4	No	3	4	No	3	4	No	2	4	2,25	4

* Only in case they did not create the BIM model themselves. Otherwise the required effort would be lower

Table C2: Scoring and validation of the impact versus effort matrix



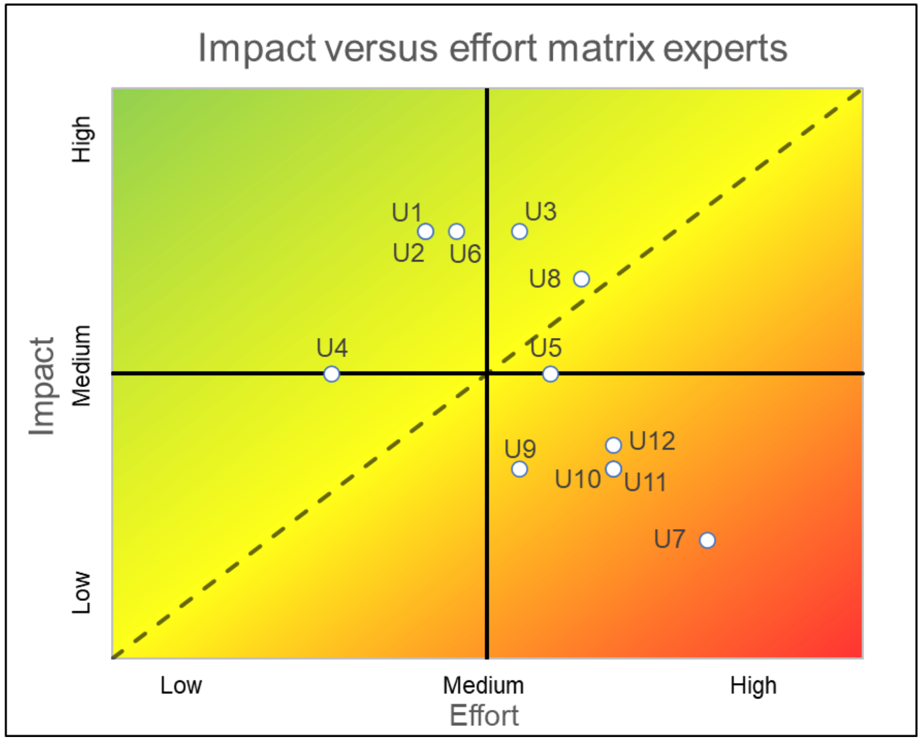


Figure C1: Scoring and validation of the impact versus effort matrix

Comments made regarding the impact versus effort matrix

- "The impact of the 4D uses is highly dependent on the type of project" - Project manager 1 (acknowledge by BIM manager 1)
- "Also the effort required to apply the 4D use is dependent on the experience of the project team. At the moment the effort required is generally high" - BIM manager 1
- BIM manager 1 and BIM manager 2 both mentioned that the effort for some of the 4D uses can be lowered when applied as a cluster. BIM manager 1 gave an example: "4D clash detection is never applied as an individual 4D use" - BIM manager 1
- "The experience of the employees is growing, so the required effort is lower and the effort will continue to decline" – Project manager 2
- "The availability of experienced employees is a factor that should be considered in ranking the effort of the 4D uses in the matrix" - Project manager 2

Appendix C.3: Configurations of 4D uses

1. Initial configuration

The initial results are given in Table C3. By combining 4D uses into configurations, the number of available 4D solution is reduced from 12 to 9. For a large share of the 4D uses, there was no common theme available.

#	4D configuration	Combination of these 4D uses	Comments
1	Design and schedule understanding	Stakeholder communication with the 4D model, team communication with the 4D model	Their purpose is different, but when the 4D model is already developed, there is little effort required to do the other.
2	Risk mitigation	Team communication with the 4D model, 4D clash detection, 4D constructability management, 4D safety management	All these 4D uses contribute towards a more complete risk analysis. These risks imply possible failure costs due to design errors, planning mistakes or safety hazards
3	Planning construction phasing sequence	4D site layout, 4D site layout with temporary works, Concrete pouring schedule with 4D	The addition of the temporary works required the existence of 4D site layout. The concrete pouring schedule would make this step more complete
4	Constructability review	4D constructability management, 4D safety management	The addition of 4D safety management offers a more complete constructability review
5	Monitoring	4D progress monitoring with point cloud scanning	No common theme found with other uses
6	On-site safety management	4D safety management	No common theme found with other uses
7	Maintenance	4D maintenance tasks	No common theme found with other uses
8	Quality control	Quality control with 4D	No common theme found with other uses
9	Decommissioning alternatives evaluation	Decommissioning alternatives evaluation with 4D	No common theme found with other uses

Table C3: List of configurations of 4D uses where a common theme can be recognized

1. **Testing and validating the configurations in the expert session**

The configurations as listed above were tested and validated using expert opinion during the expert session. The results are shown in Table C4.

#	4D configuration	Combination of these 4D uses	Agree (yes/partly/no)				Comments
			Project manager 1	Project manager 2	BIM manager 1	BIM manager 2	
1	Design and schedule understanding	Stakeholder communication with the 4D model, team communication with the 4D model	Yes	Yes	Yes	Yes	
2	Risk mitigation	Team communication with the 4D model, 4D clash detection, 4D constructability management, 4D safety management	Yes	Partly	Yes	Yes	Project manager 2: Would consider not classifying risk mitigation as an individual configuration, but as part of the constructability review
3	Planning construction sequence	4D site layout, 4D site layout with temporary works, Concrete pouring schedule with 4D	Yes	Yes	Partly	Partly	BIM manager 2: Decommissioning alternatives evaluation should be part of this configuration Project manager 2: Concrete pouring schedule with 4D could also alternatively be asphalt pouring schedules
4	Constructability review	4D constructability management, 4D safety management	Yes	Yes	Yes	Yes	BIM managers 1 and 2: This configuration is connected to the planning construction phasing sequence as part of a feedback loop. The output of the constructability review is routed back and used as input for the planning of the construction phasing sequence
5	On-site safety management	4D safety management, 4D site layout, 4D site layout with temporary works	Yes	Yes	Yes	Yes	Project manager 2: Is in his view part of the constructability review
6	Monitoring	4D progress monitoring with point cloud scanning	Yes	No	Yes	Partly	Project manager 2: Does not believe in the value of using 4D to monitor the progress of infrastructure projects, because a point cloud does not indicate whether something has been built correctly
7	Maintenance	4D maintenance tasks	Partly	Yes	Yes	Partly	Project manager 1: The quality aspect should be part of this configuration BIM manager 2: This should be part of the constructability review
8	Quality control	Quality control with 4D	Yes	No	Yes	Partly	BIM manager 2: This should be part of the monitoring
9	Decommissioning alternatives evaluation	Decommissioning alternatives evaluation with 4D	Yes	Yes	Yes	Partly	

Table C4: Testing and validating the configurations in the expert session

3. Adjustments made based on results expert session and impact versus effort matrix

Using the results from step 2 and the impact versus effort matrix from Appendix C.1, adjustments were made, as can be seen in Table C5.

#	4D configuration	Combination of these 4D uses	Adjustments	Comments
1	Design and schedule understanding	Stakeholder communication with the 4D model, team communication with the 4D model	Added: none Removed: none	Validated by 4/4 experts and all uses scored well on the impact versus effort matrix (above the diagonal line)
2	Risk mitigation	Team communication with the 4D model, 4D clash detection, 4D constructability management, 4D safety management	Added: none Removed: none	Validated by 3/4 experts and all uses scored well on the impact versus effort matrix (above the diagonal line)
3	Planning construction sequence	4D site layout, ~~4D site layout with temporary works, concrete pouring schedule with 4D~~, 4D constructability management, 4D safety management	Added: 4D constructability management, 4D safety management Removed: 4D site layout with temporary works, concrete pouring schedule with 4D	Validated by 2/4 experts and 4D site layout scored well on the impact versus effort matrix (above the diagonal line). This configuration is connected to constructability review as a feedback loop and is therefore combined into one configuration
4	~~Constructability review~~	~~4D constructability management, 4D safety management~~	Added: none Removed: 4D constructability management, 4D safety management	This configuration is closely connected to planning the construction sequence and is therefore combined into one configuration
5	On-site safety management	4D safety management, 4D site layout, ~~4D site layout with temporary works~~	Added: none Removed: 4D site layout with temporary works	Validated by 4/4 experts and all uses scored good on the impact versus effort matrix (above the diagonal line), except 4D site layout with temporary works (below the diagonal line)
6	~~Monitoring~~	~~4D progress monitoring with point cloud scanning~~	Added: none Removed: 4D progress monitoring with point cloud scanning	4D use scored poor on the impact versus effort matrix (below the diagonal line)
7	~~Maintenance~~	~~4D maintenance tasks~~	Added: none Removed: 4D maintenance tasks	4D use scored poor on the impact versus effort matrix (below the diagonal line)
8	~~Quality control~~	~~Quality control with 4D~~	Added: none Removed: quality control with 4D	4D use scored poor on the impact versus effort matrix (below the diagonal line)
9	~~Decommissioning alternatives evaluation~~	~~Decommissioning alternatives evaluation with 4D~~	Added: none Removed: decommissioning alternatives evaluation with 4D	4D use scored poor on the impact versus effort matrix (below the diagonal line)

Table C5: Adjustments made based on results expert session and impact versus effort matrix

APPENDIX D: TRANSLATING REASONS AND PROJECT CHARACTERISTICS TO CONDITIONS

In Appendix D, the intermediate steps are given in terms of translating the reasons and project characteristics gathered using literature and case studies to the conditionals. This is presented in Table D1, where the first until the fifth column represents the gathered data from literature and case studies and the sixth column represents the usage of this data. The arrows indicate whether or not this data is used and in which conditional this data is present.

4D use	**Data from literature study**	**Data from case studies**			**Usage of collected date**
	Reasons to apply 4D use	Reasons to apply 4D use	Reasons to not apply 4D use	4D use is relevant for these project characteristics	Apply under these conditions, where the score indicates the attractiveness of the 4D use
Stakeholder communication with the 4D model (U1)	· Help other engineers and non-engineers involved who are likely to be affected by the project (stakeholders) understand the design complexities and the steps required to complete the project (Khwaja & Schmeits, 2014) → Yes, U1C2	· Build stakeholders' confidence in the design using a visualization → Yes, U1C3 · Share strategic information with stakeholders → Partly, is added value that is included in all conditions	· On some occasions, it not possible to communicate with the stakeholders using the 4D model, because of contractual restrictions → Yes, U1C1	Contractual characteristics (PC3) → Yes, U1C1 Public interest (PC7) → Yes, U1C2 Complex design and sequence (PC6) → Yes, U1C2	U1C1: IF (communication with stakeholders using the 4D model is allowed) Score of U1 += 1; U1C2: IF (there are stakeholders that should understand the design complexities and the construction sequence more easily) Score of U1 += 1; U1C3: IF (increased stakeholders' confidence in the design of the contractor is desired) Score of U1 += 1; ELSE (application of U1 disadvised) Nested conditional because U1 is not interesting if the contractor is not allowed to use the 4D model as a communicational tool with stakeholders
Team communication with the 4D model (U2)	· Using a 4D model to support the communication of construction and design details (Hartmann et al., 2007) → Partly, communication of construction and design details is part of all conditions · Discuss the upcoming activities on-site during construction in daily/weekly/monthly team meetings (Umar et al., 2015) → Partly, is part of U2C2 and U2C3 but not explicitly on-site	· Visualize and communicate ideas in multidisciplinary teams where team members work on the same design → Yes, U2C1 · Discuss tight schedule of activities, involving train traffic disturbance, using animations or slideshows → Yes, U2C3 · Visualize and discuss ideas of the complex sequencing → Yes, U2C2	No data	Tight schedule (PC5) → Yes, U2C3 Complex design and sequence (PC6) → Yes, U2C2	U2C1: IF (the project design is composed of multiple disciplines) Score of U2 += 1; U2U2: IF (the project team should understand the design complexities and the construction sequence more easily) Score of U2 += 1; U2C3: IF (the project has to be delivered on a tight schedule of activities) Score of U2 += 1; ELSE (application of U2 disadvised)

4D clash detection (U3)	· Preventing delays caused by conflicts in the design coordination of multiple parties by combining their different schedules into a 4D model (Hartmann et al., 2007; Trebbe et al., 2015) → Yes, U3C3	· Determine conflicts within the schedule that could significantly affect ongoing activities → Yes, U3C3 · When clashes are discovered in the process of creating 4D visualizations, they can be used as feedback in improved versions of the schedule → Yes, U3C2	· When there is no interest in spatial temporal-based clashes and only clashes between objects → Yes, U3C1	Tight site conditions (PC4) → Yes, U3C1 Complex design and sequence (PC6) → Yes, U3C1	U3C1: IF (there will be more parties working within a restricted space) Score of U3 += 1; U3C2: IF (workflow conflicts are discovered in the process of creating the 4D visualization) Score of U3 += 1; U3C3: IF (there are possible workflow conflicts due to separated and different contractor schedules) Score of U3 += 1; ELSE (application of U3 disadvised) Nested conditional because U3 concerns workflow clashes, which means U3 is only interesting if multiple parties are having different activities within the same restricted space
4D site layout (U4)	· Support the planning of a number of different construction site layouts for different phases, involving changing cranes positions, storage areas, and accesses to the dynamic site (Guerriero et al., 2018) → Yes, U4C1	· Get insight into the logistical issues → Yes, U4C3 · Find spatial solutions when dealing with tight site conditions → Yes, U4C2	· When there is no time available to design the site layout in 4D → No, insufficient time available is a reason to neglect a 4D use but is not necessarily a condition that is specifically linked to this 4D uses	Tight site conditions (PC4) → Yes, U4C2 Tight schedule (PC5) → Yes, U4C3	U4C1: IF (a number of different site layouts need to be planned for different phases) Score of U4 += 1; U4C2: IF (spatial solutions are required for the limited available site layout) Score of U4 += 1; U4C3: IF (more insight into logistical issues is needed) Score of U4 += 1; ELSE (application of U4 disadvised)
4D constructability management (U6)	· Simulating alternative construction sequence to evaluate the overall constructability of the design (Bolshakova et al., 2018) → Yes, U6C1 · Using the 4D visualization as a project management technique for reviewing construction processes from start to finish during the pre-construction stages (Hartmann et al., 2007) → Yes, U6C3	· Ensure a more reliable and safe design → Yes, U6C2 · Get better insight into design and planning ideas at an early stage of the project → Yes, U6C3 · Get more insight into the project risks → Yes, U6C2	No data	Complex design and sequence (PC6) → Yes, U6C1	U6C1: IF (alternative construction sequences should be simulated to evaluate the overall constructability of the design) Score of U6 += 1; U6C2: IF (more insight into the project risks is needed) Score of U6 += 1; U6C3: IF (more insight into design and planning ideas of the project is needed at an early stage) Score of U6 += 1; ELSE (application of U6 disadvised)
4D safety management (U8)	· Reduce collision risk of moving or rotating machinery (Hu et al., 2011) → Yes, U8C4	· To visualize safety zones over time and support determining measures for	· Requires a high LOD, that is often not attainable in the tender stages → Yes, U8C1	Uncertainties underground (PC8) → Yes, U8C4 Tight site conditions (PC4)	U8C1: IF (the project stage is not the tender stages) U8C2: IF (safety awareness among project participants has to be increased)

	· Requires a higher LOD where the 4D model describes activities on a daily level (Choe & Leite, 2017) → Yes, U8C1	activities in dangerous areas → Yes, U8C3 · Get insight into the safety risks during construction and excavation activities → Yes, U8C4		→ Yes, U8C4 Public interests (PC7) → Partly, the public could be considered as a project participant in U8C2	Score of U8 += 1; U8C3: IF (the design has to consider safety zones over time) Score of U8 += 1; U8C4: IF (the project is concerned with high safety risks during construction and excavation activities that should be visualized) Score of U8 += 1; ELSE (application of U8 disadvised) Nested conditional because U8 required a higher LOD at a daily level, which is often not attainable in the tender stages

Table D1: Translating the collected data from literature and case studies into conditionals

APPENDIX E: QUICK-SCAN TOOL IN EXCEL

In Appendix E, additional explanation is given on how the quick-scan tool is designed in Excel that is not described in the main text (section 5.3). This includes the translation of conditionals into questions, set-up of the questionnaire and the scoring and ranking of the results in Excel. All of the content of the Excel file is visualized by using screenshots.

Appendix E.1: Translating of conditionals to questions

Link	Conditionals	Questions

General feasibility of 4D BIM	IF (the project team is experienced working with 4D)
	Score of 4D BIM += 1;
	IF (a usable point cloud and/or 3D model is already supplied by the client)
	Score of 4D BIM += 1;
	IF (the project team is working with a 3D model)
	Score of 4D BIM += 1;
	IF (the SBS and WBS project structures are applied in the project
	Score of 4D BIM += 1;
	IF (4D is a strategic ambition for the project)
	Score of 4D BIM += 1;
	ELSE (use of 4D BIM not advised)
		Q2 Is the project team experienced working with 4D BIM?
		Q3 Will the project team be working with a 3D model?
		Q4 Did the client provide the project team a point cloud and/or 3D model and is it useable?
		Q5 Is 4D a strategic ambition for the project?
		Q6 Are the SBS and WBS project structures applied in the project?

Stakeholder communication with the 4D model (U1)	IF (communication with stakeholders using the 4D model is allowed)
	Score of U1 += 1;
	IF (there are stakeholders that should understand the design complexities and the construction sequence more easily)
	Score of U1 += 1;
	IF (increased stakeholders’ confidence in the design of the contractor is desired)
	Score of U1 += 1;
	ELSE (application of U1 disadvised)
		Q7 Is communication with stakeholders (external parties) by using visualizations allowed during the project? (In case "No" is selected, then the questionnaire will skip to Q10)
		Q8 Are there stakeholders that should understand the design complexities and the construction sequence more easily?
		Q9 Is increased stakeholders’ confidence in the design of the contractor desired for this project?

Team communication with the 4D model (U2)	IF (the project design is composed of multiple disciplines)
	Score of U2 += 1;
	IF (the project team should understand the design complexities and the construction sequence more easily)
	Score of U2 += 1;
	IF (the project has to be delivered on a tight schedule of activities)
	Score of U2 += 1;
	ELSE (application of U2 disadvised)
		Q10 Is the project design composed of multidisciplinary systems components?
		Q11 Should project team members understand the design complexities and the construction sequence more easily?
		Q12 Does the project has to be delivered on a tight schedule of activities?

4D clash detection (U3)	IF (there will be more parties working within a restricted space)
	Score of U3 += 1;
	IF (workflow conflicts are discovered in the process of creating the 4D visualization)
	Score of U3 += 1;
	IF (there are possible workflow conflicts due to separated and different contractor schedules)
	Score of U3 += 1;
	ELSE (application of U3 disadvised)
		Q13 Will there be more parties working within a restricted space? (In case "No" is selected, then the questionnaire will skip to Q16)
		Q14 Are there workflow conflicts discovered in the process of creating the 4D visualisation?
		Q15 Are there possible workflow conflicts due to separated and different contractor schedules?

4D site layout (U4)	IF (a number of different site layouts need to be planned for different phases)
	Score of U4 += 1;
	IF (spatial solutions are required for the limited available site layout)
	Score of U4 += 1;
	IF (more insight into logistical issues is needed)
	Score of U4 += 1;
	ELSE (application of U4 disadvised)
		Q16 Are there a number of different site layouts that need to be planned for different phases?
		Q17 Are there spatial solutions required for the limited available site layout?
		Q18 Is more insight into logistical issues needed?

4D constructability management (U6)	IF (alternative construction sequences should be simulated to evaluate the overall constructability of the design)
	Score of U6 += 1;
	IF (more insight into the project risks is needed)
	Score of U6 += 1;
	IF (more insight into design and planning ideas of the project is needed at an early stage)
	Score of U6 += 1;
	ELSE (application of U6 disadvised)
		Q19 Are there a number of alternative construction sequences that should be simulated to evaluate the constructability of the design?
		Q20 Is more insight into the project risks needed?
		Q21 Is more insight into design and planning ideas of the project needed at an early project stage?

4D safety management (U8)	IF (the project stage is not the tender stages)
	IF (safety awareness among project participants has to be increased)
	Score of U8 += 1;
	IF (the design has to consider safety zones over time)
	Score of U8 += 1;
	IF (the project is concerned with high safety risks during construction and excavation activities that should be visualized)
	Score of U8 += 1;
	ELSE (application of U8 disadvised)
		Q1 For what project stages is the assessment made?
		Q22 Should safety awareness among project participants be increased?
		Q23 Does the design has to consider safety zones that change over time?
		Q24 Is the project concerned with high safety risks during construction and excavation activities that should be visualized?

Table E1: Translating the conditionals into questions

Appendix E.2: Set-up of the questionnaire in Excel

The Excel document of the quick-scan tool consists of two worksheets: the questionnaire and the results + processing. The Figures E1 until E6 below provide screenshots of the content of the first worksheet. This includes a brief description that concerns instruction on how the tool should be used, the purpose of the tool and when the tool should be used. In this description, it is also mentioned that the file makes use of macros. To replicate the conditionals in Excel, macros were needed to hide rows based on given answers as this action is not a standard function of Excel. The macros are programmed in Visual Basics for Application (VBA) as part of Excel. It consisted of code linked to the option buttons of Q1, Q7 and Q13.

The code for Q7 is provided in the box below, which is almost identical to Q1 and Q13. OptionButton54 concerns the “No” option, OptionButton108 the “Partly” option and OptionButton114 the “Yes” option. If the “No” option (Case Is = 1) is selected, then the rows that concern Q8 and Q9 are hidden in the worksheet. If this is not the case (Case Is = -4146), then no action is performed.

```
'Q7
Sub OptionButton54_Click()
Dim shp As Shape
Set shp = ActiveSheet.Shapes("Option Button 54")

Select Case shp.ControlFormat.Value
        Case Is = -4146
            Rows("67:84").EntireRow.Hidden = False
        Case Is = 1
            Rows("67:84").EntireRow.Hidden = True
End Select
End Sub

Sub OptionButton108_Click()
Dim shp As Shape
Set shp = ActiveSheet.Shapes("Option Button 108")

Select Case shp.ControlFormat.Value
        Case Is = -4146
            Rows("67:84").EntireRow.Hidden = True
        Case Is = 1
            Rows("67:84").EntireRow.Hidden = False
End Select
End Sub

Sub OptionButton114_Click()
Dim shp As Shape
Set shp = ActiveSheet.Shapes("Option Button 114")

Select Case shp.ControlFormat.Value
        Case Is = -4146
            Rows("67:84").EntireRow.Hidden = True
        Case Is = 1
            Rows("67:84").EntireRow.Hidden = False
End Select
End Sub
'End of Q7
```

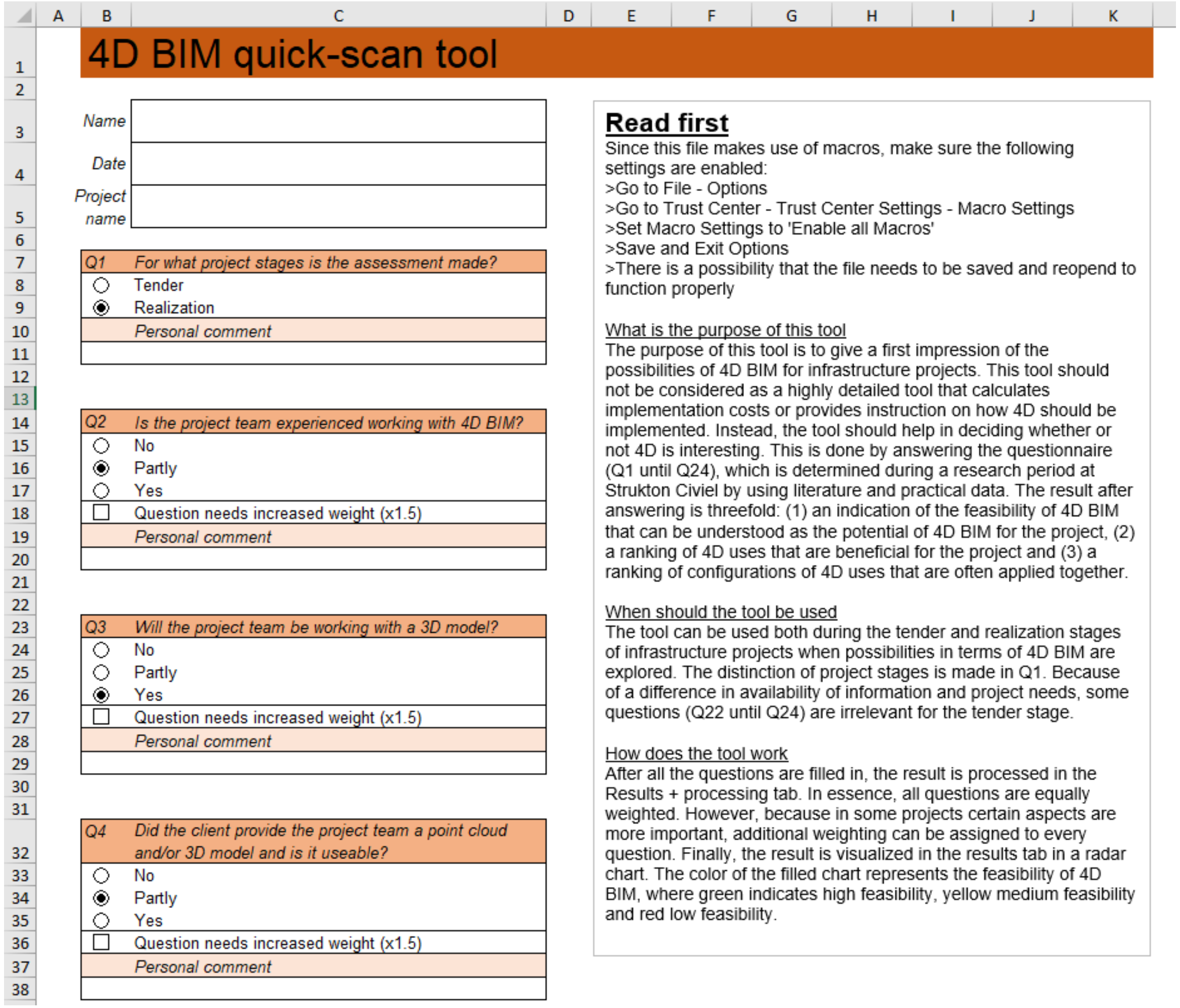


Figure E1: Screenshot of quick-scan questionnaire (Q1-Q4) and tool instruction in Excel

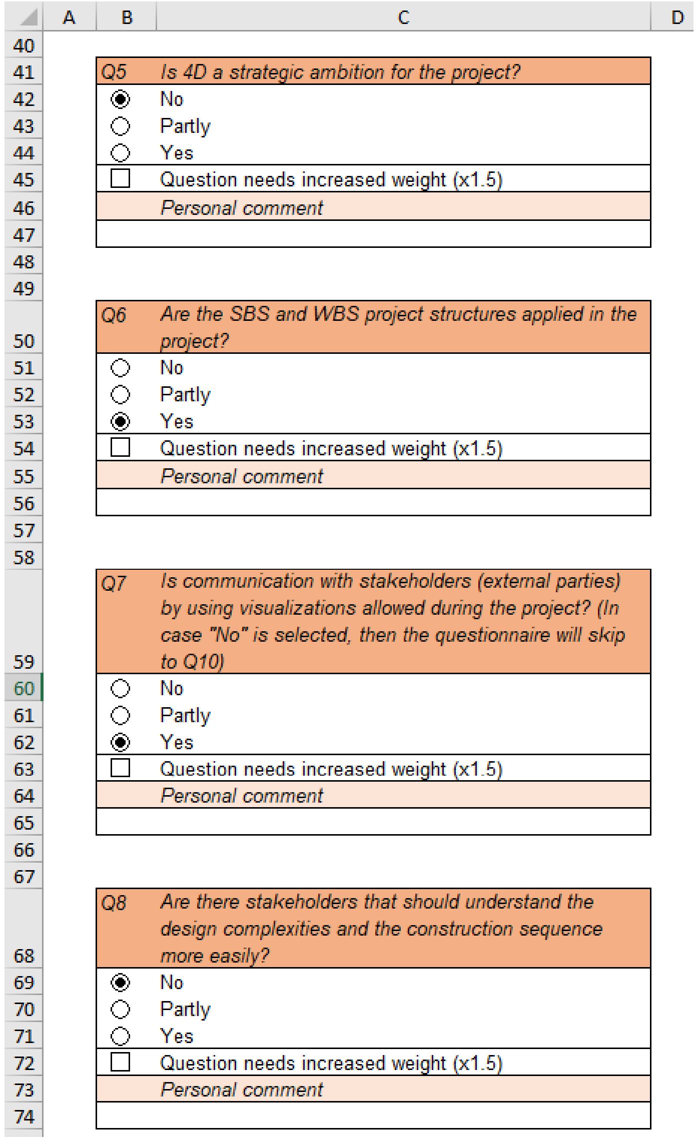
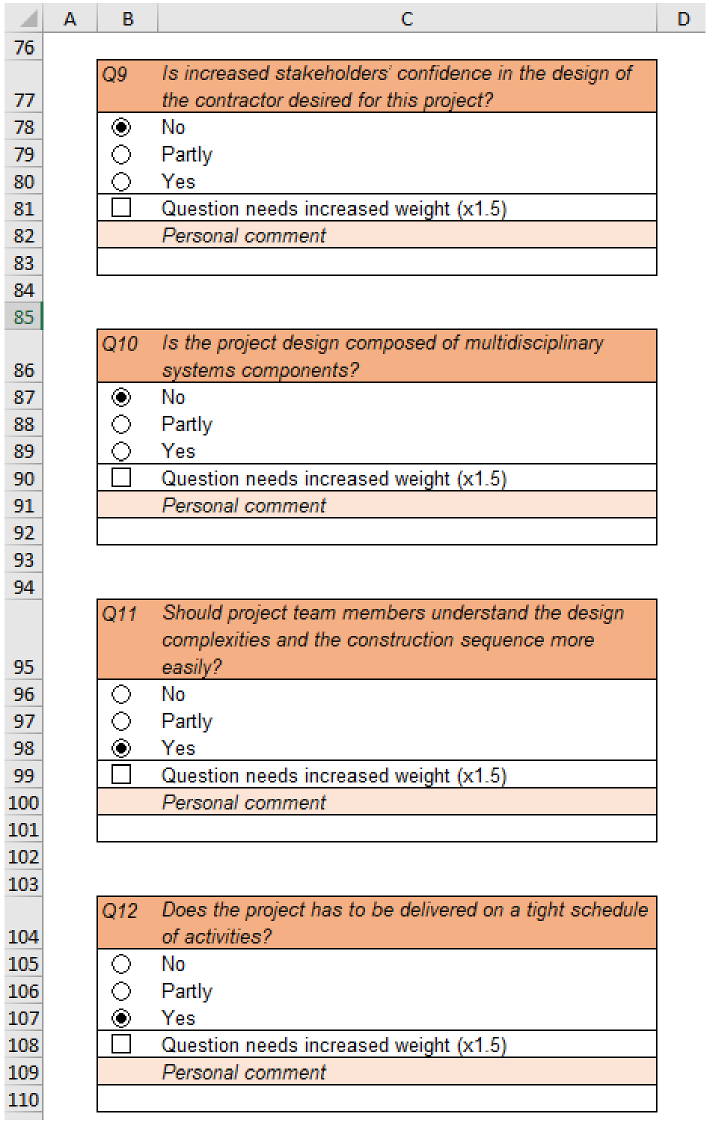


Figure E2: Screenshot of quick-scan questionnaire (Q5-Q8) in Excel



Q9 *Is increased stakeholders' confidence in the design of the contractor desired for this project?*

- (•) No
- ( ) Partly
- ( ) Yes
- ☐ Question needs increased weight (x1.5)

Personal comment

Q10 *Is the project design composed of multidisciplinary systems components?*

- (•) No
- ( ) Partly
- ( ) Yes
- ☐ Question needs increased weight (x1.5)

Personal comment

Q11 *Should project team members understand the design complexities and the construction sequence more easily?*

- ( ) No
- ( ) Partly
- (•) Yes
- ☐ Question needs increased weight (x1.5)

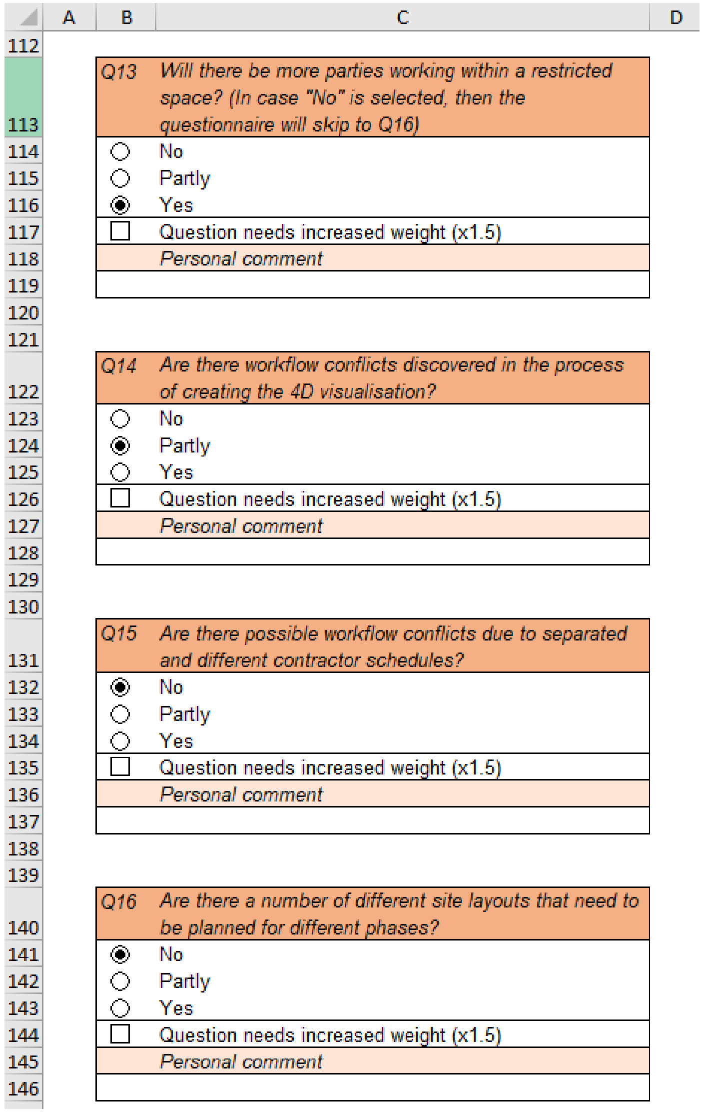
Personal comment

Q12 *Does the project has to be delivered on a tight schedule of activities?*

- ( ) No
- ( ) Partly
- (•) Yes
- ☐ Question needs increased weight (x1.5)

Personal comment

Figure E3: Screenshot of quick-scan questionnaire (Q9-Q12) in Excel



Q13 *Will there be more parties working within a restricted space? (In case "No" is selected, then the questionnaire will skip to Q16)*

- ( ) No
- ( ) Partly
- (•) Yes
- ☐ Question needs increased weight (x1.5)

Personal comment

Q14 *Are there workflow conflicts discovered in the process of creating the 4D visualisation?*

- ( ) No
- (•) Partly
- ( ) Yes
- ☐ Question needs increased weight (x1.5)

Personal comment

Q15 *Are there possible workflow conflicts due to separated and different contractor schedules?*

- (•) No
- ( ) Partly
- ( ) Yes
- ☐ Question needs increased weight (x1.5)

Personal comment

Q16 *Are there a number of different site layouts that need to be planned for different phases?*

- (•) No
- ( ) Partly
- ( ) Yes
- ☐ Question needs increased weight (x1.5)

Personal comment

Figure E4: Screenshot of quick-scan questionnaire (Q13-Q16) in Excel

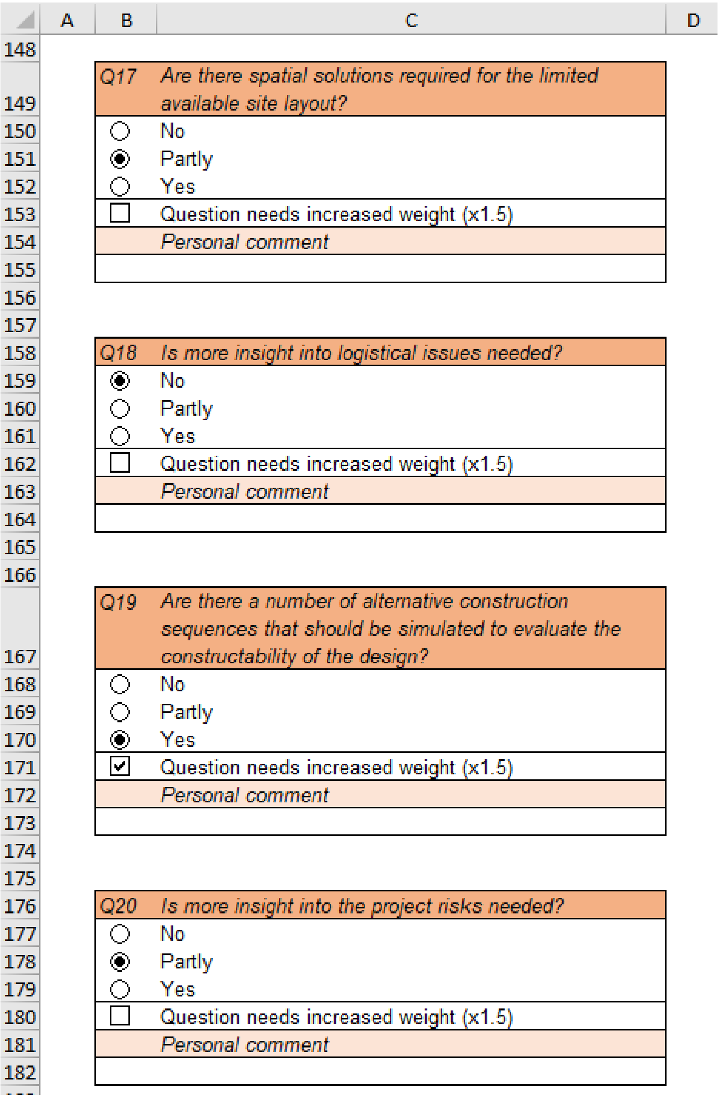


Figure E5: Screenshot of quick-scan questionnaire (Q17-Q20) in Excel

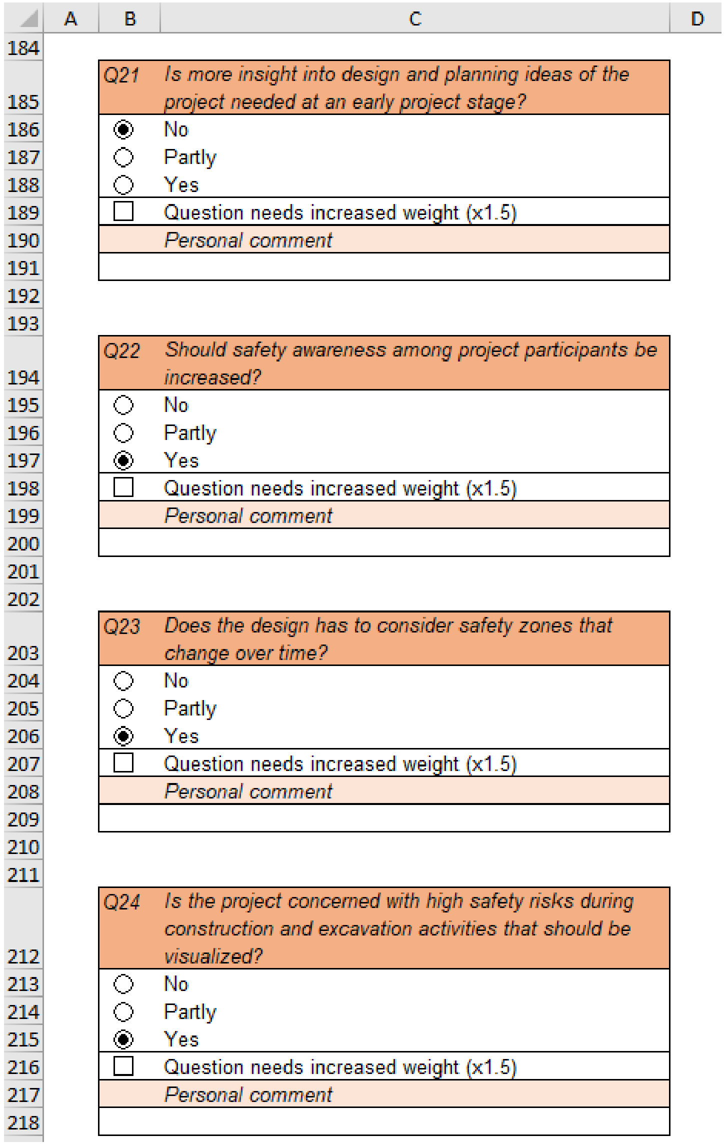


Figure E6: Screenshot of quick-scan questionnaire (Q21-Q24) in Excel

Appendix E.3: Scoring and ranking in Excel

After the questionnaire is answered, the second worksheet (results + processing) provides the results. Figures E7 until E10 on the following pages provide screenshots of the content of the second worksheet.

Figure E7 provides an overview of the results concerning the three components: (1) an indication of the feasibility of 4D BIM for the project, (2) a ranking of 4D uses that are beneficial for the project and (3) a ranking of configurations of 4D uses that are often applied together. The resulting score for every component is expressed as a percental match to the project needs that can be seen in the three tables. The score of the first and second components is visualized as a radar diagram. The colour of the radar polygon indicates the feasibility of 4D BIM, where green indicates high feasibility, yellow medium feasibility and red low feasibility. The three colours are determined based on the aggregated feasibility score, where lower than 33,33% results in a red colour, between 33,33% and 66,66% in a yellow colour and higher than 66,66% in a green colour.

Figures E8 until E10 show the processing of the results. The feasibility of 4D BIM is linked to five questions (Q2 until Q6) and the 4D uses to the other nineteen questions (Q7 until Q24). Every 4D use is linked to three individual questions, which is done by using the *Question relevant?* column next to each 4D use. If one of these three questions is answered with "Yes" and no additional weight is assigned by the user, then the 4D use scores 1 x (1/3) = 33%. If the user considers this question as more important and assigns additional weight, then the other two questions should be adjusted accordingly by aggregating the complete weight. Otherwise, the final score could exceed 100%. Therefore, the score changes to 1,5 x (1/3,5) = 43%.

Most of the results are automatically updated in the worksheet dependent on the answers given in the questionnaire through the standard functions of Excel. However, the colour of the radar diagram had to be programmed in VBA. This code is provided in the box below, which is activated when the user switches to this worksheet. Dependent on the text or string of the F4 cell (either red, yellow or green), the RGB value of the radar polygon is changed.

```
Private Sub Worksheet_Activate()

Dim f As String
f = Range("F4")

If f = "Red" Then
    ActiveSheet.ChartObjects("Grafiek 3").Activate
    ActiveChart.FullSeriesCollection(1).Select
    With Selection.Format.Fill
        .Visible = msoTrue
        .ForeColor.RGB = RGB(255, 0, 0)
        .Transparency = 0.3
        .Solid
    End With
    With Selection.Format.Line
        .Visible = msoTrue
        .ForeColor.RGB = RGB(255, 0, 0)
```

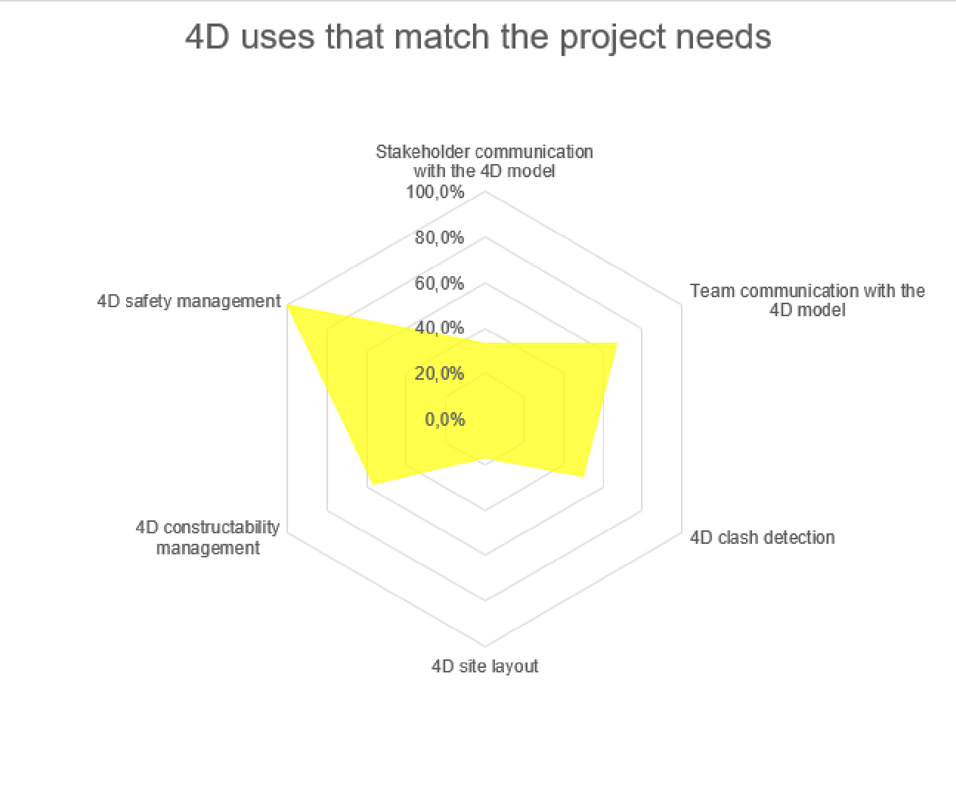
```
        .Transparency = 0.3
    End With
    ActiveChart.FullSeriesCollection(1).Select
    ActiveSheet.ChartObjects("Grafiek 3").Activate
End If

If f = "Yellow" Then
    ActiveSheet.ChartObjects("Grafiek 3").Activate
    ActiveChart.FullSeriesCollection(1).Select
    With Selection.Format.Fill
        .Visible = msoTrue
        .ForeColor.RGB = RGB(255, 255, 0)
        .Transparency = 0.3
        .Solid
    End With
    With Selection.Format.Line
        .Visible = msoTrue
        .ForeColor.RGB = RGB(255, 255, 0)
        .Transparency = 0.3
    End With
    ActiveChart.FullSeriesCollection(1).Select
    ActiveSheet.ChartObjects("Grafiek 3").Activate
End If

If f = "Green" Then
    ActiveSheet.ChartObjects("Grafiek 3").Activate
    ActiveChart.FullSeriesCollection(1).Select
    With Selection.Format.Fill
        .Visible = msoTrue
        .ForeColor.RGB = RGB(0, 255, 0)
        .Transparency = 0.3
        .Solid
    End With
    With Selection.Format.Line
        .Visible = msoTrue
        .ForeColor.RGB = RGB(0, 255, 0)
        .Transparency = 0.3
    End With
    ActiveChart.FullSeriesCollection(1).Select
    ActiveSheet.ChartObjects("Grafiek 3").Activate
End If

End Sub
```

Results



Feasibility of 4D BIM	Match	Color
Feasibility of 4D BIM	60,0%	Yellow

4D use	Match	Rank
Stakeholder communication with the 4D model	33,3%	5
Team communication with the 4D model	66,7%	2
4D clash detection	50,0%	4
4D site layout	16,7%	6
4D constructability management	57,1%	3
4D safety management	100,0%	1

Configuration	Match	Rank
Design understanding Combination of these uses: Stakeholder communication with the 4D model (U1), team communication with the 4D model (U2)	50,0%	4
Risk mitigation Combination of these uses: Team communication with the 4D model (U2), 4D clash detection (U3), 4D constructability management (U6), 4D safety management (U8)	68,5%	1
Planning construction sequence Combination of these uses: 4D site layout (U4), 4D constructability management (U6), 4D safety management (U8)	57,9%	3
On-site safety management Combination of these uses: 4D safety management (U8), 4D site layout (U4)	58,3%	2

Figure E7: Screenshot of quick-scan results overview in Excel

Processing

1. Stage

#	Question	Comments	Possible answers	Answer	Answer
Q1	For what project stages is the assessment made?	If the answer to this question is **Tender**, then no score is given to 4D safety management	1	2	Realization

2. Ranking general feasibility of 4D BIM

#	Question	Comments	Possible answers	Answer	Increased weight?	Weight	Question relevant?	Score
Q2	Is the project team experienced working with 4D BIM?		3	2	ONWAAR	1	Yes	0,100
Q3	Will the project team be working with a 3D model?		3	3	ONWAAR	1	Yes	0,200
Q4	Did the client provide the project team a point cloud and/or 3D model and is it useable?		3	2	ONWAAR	1	Yes	0,100
Q5	Is 4D a strategic ambition for the project?		3	1	ONWAAR	1	Yes	0,000
Q6	Are the SBS and WBS project structures applied in the project?		3	3	ONWAAR	1	Yes	0,200
Overall	*Final score*						5	0,600

3. Ranking of 4D uses

#	Question	Comments	Possible answers	Answer	Increased weight?	Weight	Question relevant?	Stakeholder communication with the 4D model	Question relevant?	Team communication with the 4D model
Q7	Is communication with stakeholders (external parties) by using visualizations allowed during the project? (In case "No" is selected, then the questionnaire will skip to Q10)	If the answer to this question is **not true**, then no score is given to stakeholder communication with 4D	3	3	ONWAAR	1	Yes	0,333	No	0,000
Q8	Are there stakeholders that should understand the design complexities and the construction sequence more easily?		3	1	ONWAAR	1	Yes	0,000	No	0,000
Q9	Is increased stakeholders' confidence in the design of the contractor desired for this project?		3	1	ONWAAR	1	Yes	0,000	No	0,000
Q10	Is the project design composed of multidisciplinary systems components?		3	1	ONWAAR	1	No	0,000	Yes	0,000
Q11	Should project team members understand the design complexities and the construction sequence more easily?		3	3	ONWAAR	1	No	0,000	Yes	0,333
Q12	Does the project has to be delivered on a tight schedule of activities?		3	3	ONWAAR	1	No	0,000	Yes	0,333

Figure E8: Screenshot of quick-scan with regard to the processing of the results in Excel (part 1/3)

3. Ranking of 4D uses

#	Question	Comments	Possible answers	Answer	Increased weight?	Weight	Question relevant?	Stakeholder communication with the 4D model	Question relevant?	Team communication with the 4D model
Q7	Is communication with stakeholders (external parties) by using visualizations allowed during the project? (In case "No" is selected, then the questionnaire will skip to Q10)	If the answer to this question is **not true**, then no score is given to stakeholder communication with 4D	3	3	ONWAAR	1	Yes	0,333	No	0,000
Q8	Are there stakeholders that should understand the design complexities and the construction sequence more easily?		3	1	ONWAAR	1	Yes	0,000	No	0,000
Q9	Is increased stakeholders' confidence in the design of the contractor desired for this project?		3	1	ONWAAR	1	Yes	0,000	No	0,000
Q10	Is the project design composed of multidisciplinary systems components?		3	1	ONWAAR	1	No	0,000	Yes	0,000
Q11	Should project team members understand the design complexities and the construction sequence more easily?		3	3	ONWAAR	1	No	0,000	Yes	0,333
Q12	Does the project has to be delivered on a tight schedule of activities?		3	3	ONWAAR	1	No	0,000	Yes	0,333
Q13	Will there be more parties working within a restricted space? (In case "No" is selected, then the questionnaire will skip to Q16)	If the answer to this question is **not true**, then no score is given to 4D clash detection	3	3	ONWAAR	1	No	0,000	No	0,000
Q14	Are there workflow conflicts discovered in the process of creating the 4D visualisation?		3	2	ONWAAR	1	No	0,000	No	0,000
Q15	Are there possible workflow conflicts due to separated and different contractor schedules?		3	1	ONWAAR	1	No	0,000	No	0,000
Q16	Are there a number of different site layouts that need to be planned for different phases?		3	1	ONWAAR	1	No	0,000	No	0,000
Q17	Are there spatial solutions required for the limited available site layout?		3	2	ONWAAR	1	No	0,000	No	0,000
Q18	Is more insight into logistical issues needed?		3	1	ONWAAR	1	No	0,000	No	0,000
Q19	Are there a number of alternative construction sequences that should be simulated to evaluate the constructability of the design?		3	3	WAAR	1,5	No	0,000	No	0,000
Q20	Is more insight into the project risks needed?		3	2	ONWAAR	1	No	0,000	No	0,000
Q21	Is more insight into design and planning ideas of the project needed at an early project stage?		3	1	ONWAAR	1	No	0,000	No	0,000
Q22	Should safety awareness among project participants be increased?		3	3	ONWAAR	1	No	0,000	No	0,000
Q23	Does the design has to consider safety zones that change over time?		3	3	ONWAAR	1	No	0,000	No	0,000
Q24	Is the project concerned with high safety risks during construction and excavation activities that should be visualized?		3	3	ONWAAR	1	No	0,000	No	0,000
Overall	*Final score*						3	*33,3%*	3	*66,7%*

Figure E9: Screenshot of quick-scan concerning the processing of the results in Excel (part 2/3)

	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
45																	
46	**Comments**	**Possible answers**	**Answer**	**Increased weight?**	**Weight**	**Question relevant?**	**Stakeholder communication with the 4D model**	**Question relevant ?**	**Team communication with the 4D model**	**Question relevant ?**	**4D clash detection**	**Question relevant ?**	**4D site layout**	**Question relevant ?**	**4D constructability managemen**	**Question relevant ?**	**4D safety management**
47	If the answer to this question is **not true**, then no score is given to stakeholder communication with 4D	3	3	ONWAAR	1	Yes	0,333	No	0,000	No	0,000	No	0,000	No	0,000	No	0,000
48		3	1	ONWAAR	1	Yes	0,000	No	0,000	No	0,000	No	0,000	No	0,000	No	0,000
49		3	1	ONWAAR	1	Yes	0,000	No	0,000	No	0,000	No	0,000	No	0,000	No	0,000
50		3	1	ONWAAR	1	No	0,000	Yes	0,000	No	0,000	No	0,000	No	0,000	No	0,000
51		3	3	ONWAAR	1	No	0,000	Yes	0,333	No	0,000	No	0,000	No	0,000	No	0,000
52		3	3	ONWAAR	1	No	0,000	Yes	0,333	No	0,000	No	0,000	No	0,000	No	0,000
53	If the answer to this question is **not true**, then no score is given to 4D clash detection	3	3	ONWAAR	1	No	0,000	No	0,000	Yes	0,333	No	0,000	No	0,000	No	0,000
54		3	2	ONWAAR	1	No	0,000	No	0,000	Yes	0,167	No	0,000	No	0,000	No	0,000
55		3	1	ONWAAR	1	No	0,000	No	0,000	Yes	0,000	No	0,000	No	0,000	No	0,000
56		3	1	ONWAAR	1	No	0,000	No	0,000	No	0,000	Yes	0,000	No	0,000	No	0,000
57		3	2	ONWAAR	1	No	0,000	No	0,000	No	0,000	Yes	0,167	No	0,000	No	0,000
58		3	1	ONWAAR	1	No	0,000	No	0,000	No	0,000	Yes	0,000	No	0,000	No	0,000
59		3	3	WAAR	1,5	No	0,000	No	0,000	No	0,000	No	0,000	Yes	0,429	No	0,000
60		3	2	ONWAAR	1	No	0,000	No	0,000	No	0,000	No	0,000	Yes	0,143	No	0,000
61		3	1	ONWAAR	1	No	0,000	No	0,000	No	0,000	No	0,000	Yes	0,000	No	0,000
62		3	3	ONWAAR	1	No	0,000	No	0,000	No	0,000	No	0,000	No	0,000	Yes	0,333
63		3	3	ONWAAR	1	No	0,000	No	0,000	No	0,000	No	0,000	No	0,000	Yes	0,333
64		3	3	ONWAAR	1	No	0,000	No	0,000	No	0,000	No	0,000	No	0,000	Yes	0,333
65						*3*	*33,3%*	*3*	*66,7%*	*3*	*50,0%*	*3*	*16,7%*	*3,5*	*57,1%*	*3*	*100,0%*

Figure E10: Screenshot of quick-scan concerning the processing of the results in Excel (part 3/3)

APPENDIX F: VALIDATION OF THE QUICK-SCAN TOOL (IN DUTCH)

Email gestuurd naar vier medewerkers van Strukton Civiel

Hierbij wil ik jullie vragen om het eindresultaat betreft het afwegingskader te valideren. Het afwegingskader in de vorm van een Excel tool is onderhand af en de laatste stap in het onderzoeksverslag is de tool door jullie te laten testen. Hiervoor wil ik jullie weer vragen om de tool te gebruiken voor een project waar je op dit moment mee bezig bent of anders voor een hypothetisch project. Zouden jullie daarnaast antwoord willen geven op de volgende vragen:

1. Helpt de quick-scan tool u bij het inzetten van 4D BIM in projecten? (nee/deels/ja) En waarom?
2. Geeft de tool u inzicht in de 4D toepassingen die aansluiten bij het project? (nee/deels/ja) En waarom?
3. Gaat u de tool zelf gebruiken? (nee/deels/ja) En waarom?
4. Raadt u de tool aan anderen aan? (nee/deels/ja) En waarom?
5. Moet de tool verankerd worden in de procedures van het bedrijf? (nee/deels/ja) En waarom?

Antwoorden gegeven door medewerkers

Vraag	**Expert 1: Projectleider**		**Expert 2: Bedrijfsbureau manager**		**Expert 3: BIM regisseur**		**Expert 4: Teamleider projectbeheersing / projectmanager**	
1. Helpt de quick-scan tool u bij het inzetten van 4D BIM in projecten? (nee/deels/ja) En waarom?	Ja	“Het geeft inzicht in de mogelijkheden en meerwaarde. Echter mist de investeringskant. Dus kosten versus baten om de balans te kunnen opmaken. “	Ja	“Geeft inzicht in er potentie van 4D en kaders voor toepassing mbt de startcondities en clustering van toepassingen”	Ja	“Ik heb nog wel moeite met de tool bij Safety management... Je hebt 6 "4D uses" ingesteld, maar deze komt bij mij altijd op 0 uit voor safety (zoals je hebt uitgelegd bij tenders), is het dan eerlijk om die wel bij Risk mitigation en Planning sequence mee te nemen... Ik vind van niet. Als de tender gewonnen wordt en dus project wordt zul je deze tool opnieuw kunnen invullen en dit aspect wel meenemen”	Ja	“Veel toepassingsgebieden van 4D worden niet door iedereen gezien of onderkend in de tenderfase van een project. Er kan nu op basis van objectieve vragen afgewogen worden of de toepassing van 4D meerwaarde biedt. Belangrijk punt hierbij is het aantal uren (en dus kosten). Dat deel moet toegevoegd worden aan de uitkomst van dit afwegingskader.”
2. Geeft de tool u inzicht in de 4D toepassingen die aansluiten bij het project? (nee/deels/ja) En waarom?	Ja	“Bij mij ontbreekt het inzicht in wat er voor nodig is om anders te scoren. Aan welke knoppen moet gedraaid worden om meer uit het effect te kunnen halen (dus niet om te manipuleren). Wat is in dit geval het laaghangende fruit.”	-	-	Deels	“Bij de vragen is mij onduidelijk welke nu bij elkaar horen. Hierdoor weet ik niet welke vragen nu effect hebben op het resultaat van een bepaalde 4D use"	Ja	“Het tool geeft geen inzicht in de 4D toepassing zelf, maar zo is de vraag ook niet bedoeld.”

3. Gaat u de tool zelf gebruiken? (nee/deels/ja) En waarom?	Ja	“Ik ga hem er wel op naslaan bij nieuwe werken.”	Nee	“Ik heb zelf geen projectrol. Wel ga ik de teams bevragen over de toepassing en de afweging die zij er mee maken.”	Ja	-	Ja	“Ik ga het tool bij volgende tenders gebruiken, ik laat het als hulpmiddel opnemen in ons proces management systeem (PMS). Met dit hulpmiddel kunnen alle tender- en projectmanagers een advies krijgen in of 4D van toegevoegde waarde kan zijn zonder dat ze er zelf veel ervaring mee hebben. Hiermee dragen we bij aan het niet missen van kansen die in projecten zitten.”
4. Raadt u de tool aan anderen aan? (nee/deels/ja) En waarom?	Deels	“Nog niet direct. Voor mij is deze nog niet af/ sluit niet geheel aan bij mijn behoefte. Ik zou bijvoorbeeld inzicht willen hebben in een optiepakket voor de uitwerking van een 4D programma. Dit om inzicht te krijgen in opbrengsten (dit is onder schot) versus de kosten/impact op aansturing/capaciteit die geleverd moet worden etc.”	Ja	“Is een goed hulpmiddel om een inhoudelijk gesprek te voeren over de toepassing van 4D binnen het projectteam.”	Dee ls	“Om een projectmanager te overtuigen zal je ook moeten kunnen aangeven wat de kosten zullen zijn.”	Ja	“Ik ga dit tool verankeren in het PMS en uitdragen via het domein BIM 3D/4D. Zij kunnen de werkwijze verder uitrollen in de organisatie van Strukton Civiel.”
5. Moet de tool verankerd worden in de procedures van het bedrijf? (nee/deels/ja) En waarom?	Nee	“Wel goed om te delen. Eerder zou ik een project aanwijzen om als ‘investering’ te doen zodat dit van onderaf uit de organisatie ervaren gaat worden.”	Ja	“Moet onderdeel zijn van het proces als een hulpmiddel”	-	“Op den duur zal het mooi zijn als we deze tool kunnen verankeren in onze processen.”	Ja	“Zie vraag 3 en 4.”

Tabel F1: Antwoorden per expert als onderdeel van de validatie